

Redesign Methodology for Cost Effective Assembly of Aerospace Structures

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I hereby declare that this dissertation is all my own work, except as indicated in the text

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Abstract

The research addresses the topic of design for assembly from an aerospace structures perspective. Aerospace assembly has traditionally taken secondary important to aircraft performance. This approach has been validated through healthy sales, most recently demonstrated in the Single Aisle market. However, in recent times, design for assembly has become more important. There are two main drivers behind this shift in focus. The first is a desire from aircraft manufacturers to maximise profits on existing aircraft orders through redesign. The second is the future outlook of aircraft sales, estimated to be in the trillions of dollars 2035**.** Aircraft manufacturers have therefore recognised that optimising their manufacturing system is critical lest market share is lost to emerging aircraft manufacturers through an inability to meet rising demand.

Three methods are then developed to provide design for assembly indicators for development decisions. The underpinning methodology behind these methods is a data driven approach. This is that cost saving decisions can be made using the mass of existing available data from production systems at early stages provided that key indicators are identified. The methods allow engineers to make informed decisions on design for assembly and technology development.

The first method addresses the issue of redesign. A tool is presented that relies on available data of assembly processes to make recommendations on redesign projects. The method is populated with real data and its output is compared against real business decisions. The results show that the method provides positive direction and is beneficial when filtering between costly redesign projects.

The second method addresses design for assembly at early product development. A complexity metric is developed using a combination of historical

data and known data at a particular development stage to produce a complexity metric that carries out an analysis of a full assembly system. It provides the engineer with a macro view enabling the identification of potential bottlenecks. Data from a previous product was used to demonstrate this method. The results shown were able to highlight real issues and make recommendations about technology strategy.

The final method developed in this research recognised that design for assembly and assembly technology were synergetic and should be developed together. It proposed an assembly process characterisation technique to enable future technology strategy planning at design for assembly stage. The tool was demonstrated using existing data and proposed several concepts for a future product to enable higher levels of automation and more cost effective future technology implementation.

The research concluded that there was a definite advantage in using the demonstrated methods in providing direction to an aircraft manufacturing business. In the redesign method and the complexity analysis method this was validated through comparison against real business decisions. The two methods were in line with business thinking. Also, where the redesign method was different in its advice compared with business direction, it was shown that following the advice of the method would have been beneficial to the business. It was more difficult to validate the shared platform approach method due to its results providing indicators for future decisions. Early analysis into its potential validity through technology benchmarking looked promising.

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Key Terms

DFA	Design for Assembly
DFMA	Design for Assembly and Manufacture
SOI	Standard Operating Instruction
STV	Standard Time Deviation
AEM	Assemblability Evaluation Method
AFP	Assembly Functional Presentation
PRDM	Problem Recommendation Driven Mechanism
DBPRA	Design for Assembly Product Based Redesign Approach
COTS	Commercial off the Shelf
PLM	Product Lifecycle Management
ADU	Automated Drilling Unit

1. INTRODUCTION

1.1 THE AEROSPACE ASSEMBLY SCENARIO

The aircraft industry produces long life products that have a production life in the decades of years. The two dominant commercial aircraft manufacturers, Airbus and Boeing, rely on their single aisle, shorter range products as consistent revenue streams. The Airbus A320 first flew in 1987 and the Boeing 737 first flew in 1967 (Norris, 2014). In order to reduce risk, these companies have adopted an iterative development approach to their products as opposed to regular new product introduction. This approach has been vindicated by the record sales achieved by the latest iteration of the Airbus A320, known as NEO (Airbus.com, 2014). With an extensive order book secured, aircraft manufacturers have now shifted their focus to cost reduction to maximise profits.

Assembly and Manufacturing systems have been identified as key for cost reduction. The traditional approach to manufacture and assembly optimisation has been the implementation of lean philosophy and technology insertion (Arc Advisory Group, 2011). However, a key element in optimising assembly in particular is the product itself. Retrospective major design changes to aircraft products for assembly improvement have largely been avoided previously in favour of performance optimisation. With the focus now on cost reduction, aircraft manufacturers are beginning to view Redesign for Manufacture and Assembly as a promising prospect.

However, as well as taking a backward view of DFMA, a robust method is required for future planning of product design for assembly that is directly applicable to design for assembly and manufacture.

1.2 RESEARCH MOTIVATIONS

Identifying potentially profitable redesign for assembly projects has proven to be difficult and is a major motivation for this research. Creating methods to identify weaknesses of manufacturing and assembly systems is the overarching theme..

The research is motivated through the drive to address legacy product manufacturing systems. Also, throughout the research journey the question that presented itself is how can similar situations be avoided in the future.

As briefly touched upon, the commercial aircraft market is very healthy. Particularly the single aisle market. The Airbus A320 family and the Boeing 737 family in particular are the most popular commercial aircraft in the world. As well as a brimming order book the outlook for aircraft sales in the near future is estimated to be an ever expanding market, In a report by the market research company, Frost and Sullivan (Frost and Sullivan, 2017) it is estimated that over the course of the next 20 years, 38,050 aircraft will be delivered across the world. When it is considered that there is reportedly under 30,000 aircraft in operation today this gives an indication of the potential scale of demand for aircraft (Morris, 2017).

Delivering current orders of Aircraft at a better profit is the first main motivation for this research. Design for Assembly was not mature as a concept when the current highest selling aircraft from the single aisle market were designed. Thus they suffer from design imbedded manufacturing difficulties.

However, this is not the sole reason why DFA should be taken more seriously in aircraft production. Making a better profit is important, but improving delivery time through DFA is also critical in securing market share.

In a report published by Boeing (2015), it is estimated that delivery of new aircraft will amount to a market valued at $5,570 Billion. As such, it is no surprise that

competitors to Airbus and Boeing are emerging. Bombardier Mitsubishi and Embraer, traditionally competing in a different market have recently begun challenging the lower sized single aisle market that was traditionally Airbus and Boeing territory. However, most notably, the state supported Chinese and Russian offerings are designed to compete directly with the single aisle market. It is important to note that new products mean new manufacturing lines and the likely adoption of new product development philosophies. Therefore, for a company such as Airbus, it is critical to consolidate its market share but not only by investing in its manufacturing system, but also its product development philosophy to impact that manufacturing system.

As mentioned, existing products designed in the 1980's have inherent manufacturing difficulties due to the product development philosophies of the time. A major motivation of this research is how these can be addressed. How can the more recent knowledge gained from newer products and overall industry development benefit an existing manufacturing system and product that was created in the 80's?

Moving on from existing products, it is now acknowledged that DFA is a requirement during product development. As such, simulation tools have been adopted to assist this. Another motivation of this research is to direct those simulation tools to acknowledge DFA. It is believed that this will offer a great benefit to overall product design.

The final motivation of this research is in the acknowledgement of the fact that aircraft products have long lives, so how can future technology planning be made a part of the product design and lifecycle planning process.

1.3 AIMS AND OBJECTIVES

The aim of this research is as follows:

"To provide methods and toolsets for engineers to gain rapid insight into issues relating to design for assembly in aerospace assembly systems, both on legacy products and new product development."

Rapid, in this case refers to the engineer making a decision quickly through existing data as opposed to the creation of new data which is a typically time consuming process.

The aim of this research is supported by the following objectives:

- Carry out a literature review on Design for Assembly, Redesign for Assembly, process analysis, complexity analysis and future product planning.
- Develop a new method for identifying design or process improvements on existing serial products.
- Validate this method through the application of real life case studies.
- Develop a macro analysis method that can look at a whole manufacturing system and allow the engineer to identify manufacturing system issues in both a serial production product and in a development program.
- Validate this method through the use of existing data on a serial product.
- Develop a method that combines technology planning and product design for assembly considerations for the development of the optimised manufacturing system.
- Validate this method through examples based on current product configuration modifications.

2. LITERATURE REVIEW

2.1 DESIGN FOR ASSEMBLY

Design for Assembly and Manufacture (DFMA) is a method that has been widely adopted in the development of new products. The terms “Design for Manufacture” mean the design for ease of manufacture of the collection of parts that will form the product after assembly. The terms “Design for Assembly” mean the design of the product for ease of assembly (Boothroyd et al., 2014). Before the adoption of DFMA, design engineers would typically work independently of manufacturing and assembly engineers. Boothroyd et al. (2014), state that over 70% of product cost is assigned at the development stage. Indeed the objective of DFMA is to reduce cost in the overall life of a product.

The most notable work on DFMA is that of Boothroyd et al. (2014). They pioneered the DFMA method and gave it an industrial focus. Their proposed method is to assess every component by the following three criteria:

1. During the operation of the product, does the part move relative to all other parts?
2. Must the part be of a different material than or isolated from all other parts already assembled?
3. Must the part be separated from all other parts already assembled because otherwise necessary assembly or disassembly of other separate parts would be impossible?

They demonstrate the application of this method extensively showing how part count can be reduced extensively. Further to this, they also highlight the importance of assembly sequence and direction and also demonstrate cost savings through assembly sequence planning.

However, the applications are all of small volume parts with tolerances that are more relaxed than those required in the aerospace industry. Also, the Boothroyd method is focused on part count reduction. Frey et al. (2007) carry out an in depth analysis on the effect of part count reduction in increasing product robustness. As part of this analysis they state that although part count reduction can lead to a reduction in cost, in high value components it can also lead to an increase in cost. The examples presented by Boothroyd are of relatively low value assemblies and reducing part count usually involves transferring part functionality into other components making their manufacture slightly more complex. If this approach was implemented on aircraft components then this would likely result in unmanageable escalating costs. In a redesign scenario, reducing part count is even more difficult. In the case of legacy aircraft, the infrastructure involved in manufacturing the components would also need to be updated. Suppliers of complex machined components would be required to increase their capability to accommodate additional functionality of components. Fixtures and assembly technology would also need upgrading. In this light, part count reduction is only part of a strategy to reduce assembly costs in redesign of aircraft assemblies.

Another approach to Design for Manufacture and Assembly is that of Miyakawa and Shigemara (1986). They developed the Hitachi Assemblability Evaluation Method (AEM); a tool that feeds into design to improve producibility of the product. It consists of two steps; the first is to assign quantitative data to existing assembly processes and the second is to sum these values to create an AEM score. This is then used to assess time and cost through mapping out known time and cost values against calculated AEM scores and extrapolating across. Ohashi et al. (2002) further expanded on this method by

introducing part-based cost estimation. Similar to this is the Lucas method, developed by Sealy and Corns (1992). They assigned ratings to the following:

- Functional Analysis: Interrogation of every component as to its function within the product.
- Handling Analysis: Examination of the ability to handle and position each part to achieve the correct assembly orientation.
- Fitting Analysis: Assessment of ease of holding an assembly.

In a redesign context it is difficult to make accurate estimates of cost impact due to the associated impact on delivery disruption, supplier capability development and in house infrastructure development. Also, at redesign stage, the selection of processes and technology has already taken place and decisions on technology and process selection will also include the cost of replacing infrastructure against the cost of keeping functional existing infrastructure. However, the methodologies are relevant to future product development. The analysis carried out largely focuses on small scale assemblies though. In the context of aerospace assembly, handling and fitting are vastly different fields then small volume assemblies. An example is that in a small volume assembly fitting is measured upon how easy it is for the operator to place a component into another component. In wing assembly, fitting is about lining up components that can be up to 15 m in length to a high accuracy. It makes the challenge much more difficult.

Hsu and Lin (2002) also produced a quantitative method. This method was designed to assess component accessibility during assembly. They argue that accessibility is an indicator of the probability of successfully achieving design targets within manufacturing capability. This method relies on the availability of 3D CAD models to carry out

assessments. 3D CAD models are now industry standard and thus for product development this method is highly relevant. However, in the case of legacy aircraft, the assemblies being considered for redesign are several decades old, developed before the widespread application of 3D modelling. Further, the accessibility being discussed is access to the part, or difficulty in placing components into the part. Accessibility in aircraft assembly is different; the challenges are those of line of sight and ergonomics due to the size of the assembly. Operators are required to crawl into confined spaces through access holes designed into the assembly and carry out operations in a very restrictive environment. Other areas require techniques that give operators knowledge about opposite sides of the work piece due to the size of the components preventing visual inspection. This could be in the form of advanced metrology equipment.

Stone et al. (2004) propose a product architecture based approach to DFA.

They introduce the concepts of functional basis and the method of module heuristics. The functional basis technique is used to develop a functional model of a product in a standard that can be compared to other products. A heuristic approach is then applied to that functional basis to develop a practical product architecture. This product architecture approach is illustrated below:

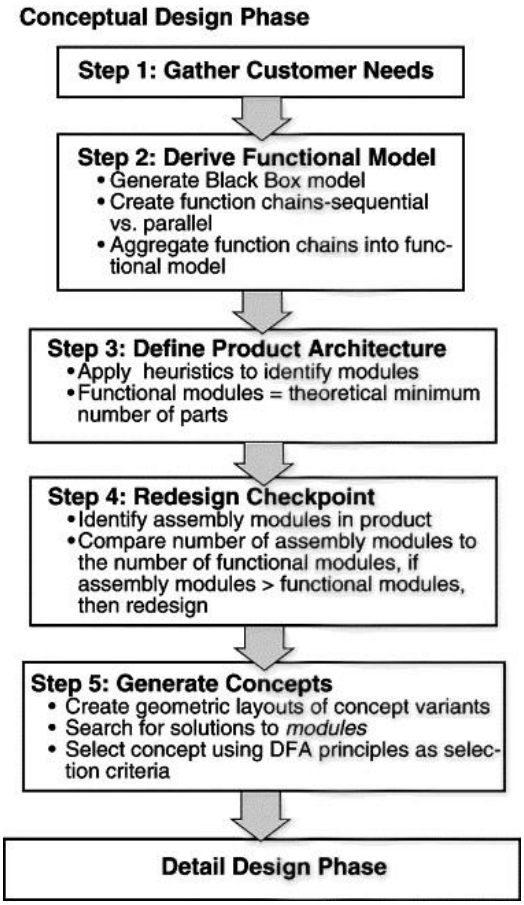


Figure 2-1 Stone et al. (2004)

They highlight that unlike traditional methods, which they refer to as post design DFA, their proposed method considers DFA at the conceptual design stage and product architecture is built around a DFA philosophy. A case study is presented where a product is analysed using a more traditional Boothroyd approach and their proposed method. The main advantage is that Stone et al. (2004) considers the function of the product as opposed to the product being a collection of parts to be reduced in number. Using this approach they were able to demonstrate a greater reduction in the number of parts. The main criticism and the contribution to knowledge presented in this work appears to be the removal of the requirement for redesign. They imply that this is a requirement of the Boothroyd method. However, the Boothroyd method implicitly states that its

objective is a multifunctional design approach that includes assembly analysis during design. Active redesign would only take place on an existing product.

The method is innovative however in its functional approach to DFA, allowing the engineer to ask the question of whether a design needs to look a certain way to achieve its functional purpose. Although the part count reduction was the focus of the case studies this is applicable to aircraft manufacture. An approach such as this will enable engineers to change traditional aircraft assembly techniques in view of achieving functional objectives.

Whitney (1988), in the Harvard Business Review, comments on DFA in the context of manufacturing by design. He says that value engineering and design for producibility are the real objectives when embarking on a DFA journey. He says that DFA cannot achieve fundamental improvements because it considers the product as a collection of parts instead of something to satisfy larger goals such as reducing costs over the life time of the product. This further emphasise the point made about part count reduction in aircraft assembly.

This will be later emphasised when a traditional Boothroyd type analysis is carried out on a wing box.

2.2 REDESIGN FOR ASSEMBLY

The tool sets and methodologies that were discussed in Chapter 2.1 dealt generally with original design. This section discusses Redesign for assembly. This subject, although it is prevalent and likely occurs in every manufacturing and assembly business, is not explored as extensively as original design for assembly. Fabricius (1994) makes the statement that industry will traditionally

favour technology insertion for manufacturing improvement in a steady state production environment.

Desa et al. (1987) acknowledged the importance of redesign. They developed a tool set and interface module that relies on historical knowledge of the original design for input into redesign. They state that the following aspects are critical when carrying out redesign:

- Development of a set of performance measures
- Good understanding of the effect of design modifications on these performance measures
- Procedures that utilise the first two points

An attempt is made to quantify these aspects and introduce them as factors into a computer interface along with design specifications such as design rules. The example presented is rudimentary but perhaps this is the earliest research in attempting to calibrate assembly requirements against functional requirements.

Similarly, Hsu and Grier (1998), also looked at redesign based on DFA. They produced a Design for Assembly Product Based Redesign Approach (DBPRA). This method combined Assembly Functional Presentation (AFP), Problem Recommendation Driven Mechanism (PRDM) and DFA. AFP is used to ascertain information about the nature of the parts and their interactions, such as mating relationships and tolerance allocations. The PRDM directs the redesign focus towards the problems identified by the DFA analysis. The result is a method where DFA issues are identified on a product and are reasoned against the functional requirements of the product to effect global design changes. The

approach aims to take advantage of frequent demand for new products in certain markets and the requirement to redesign often to meet that demand. The scenario is a new product introduction scenario and is not directly applicable to long life products undergoing optimisation redesign, such as aircraft. However the approach is suitable for development programs where due to the high value of the products testing is expensive and much of the early data will come from existing product lines. In the case studies demonstrated the DFA analysis is carried out using the Boothroyd method. This is significant because as has already been discussed the Boothroyd method is useful but not all encompassing. Therefore, although the methodology is useful in calibrating between DFA and design intent it doesn't offer specific solutions for specific scenarios of DFA application. This is in evidence in both the case studies presented; they are small volume assemblies that the Boothroyd method is designed for.

Baxter et al. (1994) introduces the concept of utilising computer aided design for automatic DFA feedback. They make the point that even in short life products, redesign is common with the German Mechanical Engineering industry reporting that 55% of so called new design was adaptive and 20% was variation on existing design. They approach the problem of redesign from an automated perspective. When existing design is under analysis, they propose that software is embedded with a functional data model that can feed back to the operator DFA requirements. This is problematic for two reasons. The relegation of manufacturing and assembly engineers and the tacit knowledge provided by that field during design phase is the exact reason that previous manufacturing generations were inefficient. Attempting to replace that tacit knowledge with a form of explicit knowledge that can be transformed into data will introduce problems. The authors allude to this in their conclusions when they state that the

applications they have developed are “only effective in conjunction with the ability of the designer to be aware of the implications of the information sup plied.” This point is emphasized in the fact that since 1994, when this paper was published reliance on software for DFA input was not common place. This researcher observed this specifically in the aerospace industry. Rather, multi-functional teams are deemed more valuable.

Rampersad (1994) looked at redesign in the context of robotic assembly. The manufacturing industry of the time was moving towards more and more automated applications and thus existing designs could bene fit from reduced assembly cost if redesigns were carried out to accommodate robots. The author introduces a simplified method for redesign using DFA called the House of DFA.

Lee (1993) and Kim and Bekey (1993) speak about applying traditional methods of DFA in redesign situations. They argue that these traditional methods of DFA are geared for original design and some modification of those methodologies will lead to a more successful redesign methodology. The two modifications they propose are the inclusion of analysis of assembly sequence as part of redesign DFA methodology and also the consideration of design rationale in the same process. They developed what is called the Backward Assembly Planner (BAP) to identify assembly problems and REVerse ENGineering (REVENGE) toolset to come up with assembly solutions. They argue that this methodology leads to a more realistic DFA outcome as the activity of assembly planning is coupled tightly with redesign. The system however does not take into account functional requirements and thus lacks the ability to make suggestions to account for major functional requirements thus limiting its scope. However, the idea of including assembly planning as part of the design process is beneficial not least because

this can help to account for cost and delivery decisions. It gives the engineer the ability to not just modify designs to alleviate assembly bottlenecks but to plan assembly activities based on delivery requirements which could be associated with assembly technology.

Lefever (1996) highlights that piece count reduction is the most effective Redesign DFA target. He approaches the issue from a reverse engineering and redesign perspective. He proposes the use of three techniques:

- Subtract and Operate Procedure: this involves going through cycles of the assembly process and removing components at each cycle to analyse whether the product can manage without that particular component. Components are then subtracted based on their necessity to the assembly and product.
- Force flow diagrams: This method documents where forces are applied during an assembly and aims to reduce the amount of force application procedures by combining components.
- Boothroyd and Dewhurst extension in which the three criteria specified in the Boothroyd and Dewhurst methodology are explored with the intention of changing the design so that parts fall out of the criteria and thus they are not required to be individual components. An example of this is a part that moves with respect to the rest of the assembly. Under the Boothroyd rules this part would be allowed as a separate component. Lefever encourages the engineer to ask the question “does the part need to move?”

The first two of these techniques are adaptive techniques that are useful for piece count reduction on typical smaller volume assemblies such as those demonstrated by Boothroyd. These techniques suffer from the same drawbacks as Boothroyds work in that piece count reduction is only the answer in certain circumstances. The final technique, which the author refers to as more of a methodology is interesting for a reason not stated by the author. Although it also advocates piece count reduction it can be turned around to ask the opposite question as well. For example, does an existing component offer a higher level of complexity and thus cost then if that component was split into multiple components?

Interestingly, Otto and Wood (1998) make the point that redesign as a tool for product optimisation is a niche research area. This view is contradicted by Baxter et al. (1994). They proposed a methodology for redesign using reverse engineering. The methodology they propose is split into three stages as shown below in Figure 2-2.

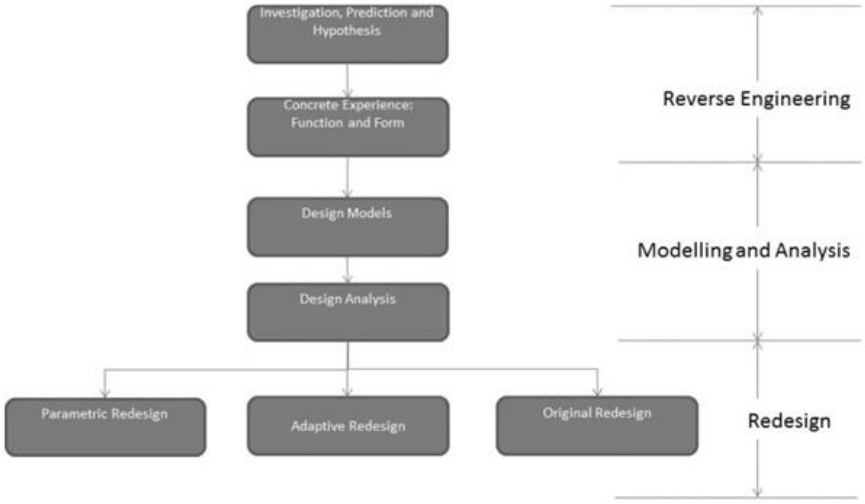


Figure 2-2 Otto and Wood, 1998 Redesign process

The research is predominantly targeted at product optimisation but the authors make the comment that the methodology is dynamic and can be modified to target optimisation of other parts of the product such as manufacturing.

Similarly, Hsu et al. (1998) proposed a Problem Recommendation Driven Mechanism (PDRM) redesign for assembly method that is initiated by a Design for Assembly Evaluation. Once the assembly targets or problems are highlighted a functional analysis is used to produce the constraints of any redesign. This method contributes some positive critical thinking into the redesign problem; however, no live industrial case studies were implemented. Additionally, the method did not account for two important aspects. The first is the cost involved in redesign and implementation, the second is that there is no account for obsolescence of technology.

Hsu et al. (1993) proposed an integrated design planning system. The aim is to use assembly planning that usually takes place after design completion, as an input into redesign. Assembly plans are analysed with respect to three contributors:

- Parallelism: Optimising activities to take place in the most efficient manner.
- Assemblability: Reducing assembly uncertainty to increase repeatability.
- Redundancy: Assessment of component indispensability looking to reduce the number of components.

In the redesign scenarios that are discussed in this study the assembly plans are already implemented and extensive line balancing has also taken place. There is however, a definite scope for assembly plan evaluation as an input into redesign for future product development as has been demonstrated.

Ghie et al. (2007) presents a redesign method that uses the Unified Jacobian-Torsor model for tolerance analysis. The method involves identifying key functional requirements and functional elements of the dimensional chain and then prioritising some functional requirements and reflecting that in the functional elements by way of tolerance allocation. The method is relevant to the type of legacy product optimisation that may be required in aerospace assembly. Critical assessment of tolerance criteria is not assessed regularly on long life products. Usually it is only assessed when there is a particular quality issue. Further, typically, tolerance issues such as gaps are addressed through time consuming shimming processes. For legacy aircraft, assigning of tolerances was carried out much before software was available to aid this. The likelihood is that there are opportunities in implementing a method such as this on existing designs. The methodology doesn't discuss a design strategy however focusing purely on tolerance allocation. This is a significant factor but does not holistically cover an approach to redesign.

Unlike other authors, it is explicitly stated that this method is intended for use on small assemblies such as precision-mechanical and electromechanical.

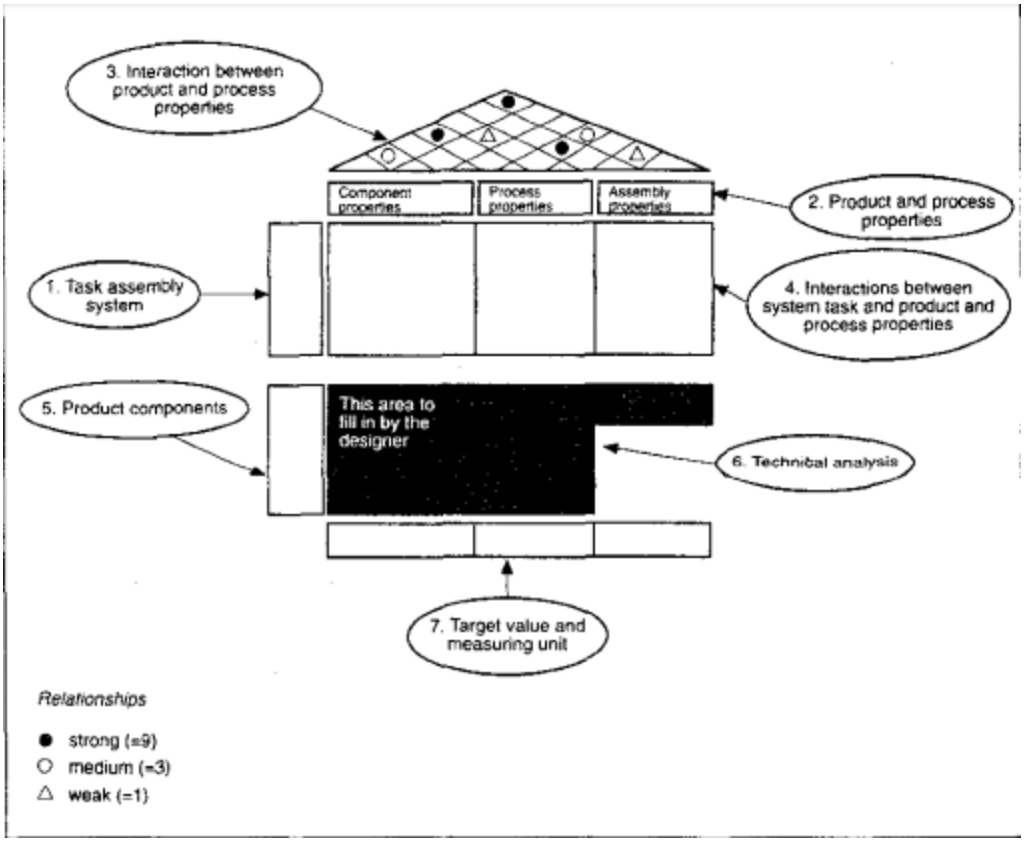


Figure 2-3 The House of DFA. (Rampersad, 1995)

Assembly processes are categorised into a set number of headings such as feeding, handling, composing, checking, adjusting and special processes. These operations are then further divided into sub operations and weighted using a factor of 1-4. The scores are summed together and this provides a difficulty rating. The problem with this method is the opposite of the problem of the software method. Although it provides an opportunity for the engineer to include tacit knowledge through the allocation of weighted factors, these are subjective to the opinion of the engineers involved. A method in between that provides both qualitative tacit knowledge input and measurable explicit knowledge input would be the ideal solution. Nevertheless, the method is novel in simplifying the DFA

process and offering a macro view of an assembly system. It is possible for engineers to analyse the impact of their decisions through this approach. This method is also not limited to the redesign scenario. It can easily be adapted for use in new product development where an active system provides consistent feedback to the engineers at every design or assembly decision.

2.3 DFA avoidance and commercial off the shelf

Commercial Off the Shelf, COTS, multi-supplier and open source options are terms often used to describe the decades long shift from proprietary to standards based automation technologies. The realty for OEM's is that there is a large amount of bespoke last generation and current generation technologies. In a report written by Peter Reynolds for the Arc Advisory Group (2011), a global market research advisory group, it is estimated that there is approximately $65 billion dollars of obsolete automation technology within the manufacturing industry. This report looks at a study carried out by ARC analysing industry strategies and practices in managing bespoke, ageing or obsolete technologies. The results of the study indicate that there is an industry shift forwards introducing COTS technology. This has a significant impact on people and resources within a plant. Maintaining legacy bespoke technology alongside the introduction of COTS technology means that certain skill sets need to be maintained and this presents future planning challenges. Further, the gradual creep of COTS technology perpetuates a cycle that is most likely to choose a COTS option in future assembly and manufacturing optimisation decisions. This is due to the reality that when such an approach is taken a business will offset some of its costs by eliminating its own tacit knowledge development. This creates a scenario where

business decisions are made without informed knowledge and thus rely on key supplier-partner relationships.

Planning for obsolescence is a complex problem. Combinations of an aging workforce, skills gap, and the effort to keep manufacturing operations running at peak performance during changes all add to the complexity of the issue. Reynolds report mainly focuses on the introduction of Automation technology and focuses on the obsolescence of those technologies. This is a challenging and widely discussed issue within the aerospace industry. An example are the main assembly Jigs used to create the wing box assemblies. Legacy fixtures have typically been large static bespoke solutions. However, some legacy programs have been in manufacture for more than several decades. As market demand increases, rate of production in the factory increases and the capacity of existing fixtures reach a maximum. The aerospace industry is typically risk averse and thus prefer lower risk proven methods.

If one notices the recent design modifications that have been implemented on the single aisle program, they are predominantly changes to optimise the product performance. The last two design modifications as mentioned previously have both been performance improvements and the results have been substantial (Airbus.com, 2014). The latest Single Aisle Aircraft iteration, A320 NEO, has amassed orders of 2600 since it was launched, taking into account that the overall order number of the Single Aisle family is 10,200 this is a substantial percentage which appears to justify the focus on performance enhancement. Compare this to the life of an older program such as the Airbus A320 or the Boeing 737 and the level of technology that is being used in wing assembly. The risk of implementing new technology is high and major manufacturers would be

reluctant to put delivery speed under threat even for a short period due to the impact this will have on overall competitiveness in the market.

The attraction to COTS is expressed concisely by Demko (1996). COTS technology has the following advantages:

- Low Cost
- Short Lead Time
- Multiple Suppliers
- Industry regulated
- Mature Design
- High Volume Production

This is why in aircraft manufacture, COTS represents a low cost low risk solution compared with a high risk, high cost redesign solution, even if the potential benefits are high. Also, COTS does not offer a long lasting competitive advantage. Even if a manufacturer is the first to utilise a technology, competitors can immediately respond by purchasing the same technology.

The paper discusses COTS in the context of military technology acquisition. Whilst relating these potential advantages, the author acknowledges that it also offers the opportunity for a reliability and logistics disaster when parts don't fall within stricter military requirements. This is directly comparable to aircraft manufacture where safety and performance requirements are drastically different from other manufacturing industries. Technologies implemented in the automotive industry, such as high robot utilisation, although mature and relatively low cost, are not appropriate in aircraft manufacture for a variety of reasons such as the greater positional accuracy requirement required during assembly.

Tran and Liu (1997) analyse COTS practice within the software industry. There are parallels in their experience with the manufacturing industry. For example they highlight that there is a risk in implementing COTS technology when the technical risk is underestimated. In software implementation this has often resulted in longer schedule delay and higher development and maintenance cost. The maintenance aspect is also relevant as it means a plant is not flexible in maintenance and assembly system support.

Mehrabi et al. (2000), approached the issue of dealing with changes to manufacturing requirements from a different perspective. Their approach was the introduction of flexible manufacturing systems. Flexible or reconfigurable manufacturing systems are designed for rapid adjustment or production capacity and functionality.

One criticism of reconfigurable manufacturing system is that they are liable to be impacted by obsolescence. The reconfigurable nature of the manufacturing system allows expansion of capacity only within the scope of that manufacturing system. If innovations outside of that manufacturing system are developed that can be beneficial then that reconfigurable system now acts as a hindrance. Reconfigurable manufacturing systems have high risks associated with them. They have higher costs associated with them and the benefit is questionable in aerospace applications due to the long life nature of the products and limited product configurations. However, even the adoption of a reconfigurable system would be a difficult task without a design or redesign for assembly input. Obsolescence is discussed in the following section.

2.4 Obsolescence management

For long life products such as aircraft, Obsolescence is a crucial factor in the consideration of Design for Assembly. According to Sandborn (2007), obsolescence can be defined as “the loss or impending loss of original manufacturers of items or suppliers of items or raw materials.” This is the traditional definition of obsolescence and its appearance is demonstrated succinctly by Bartels et al. (2012) in Figure 2-4.

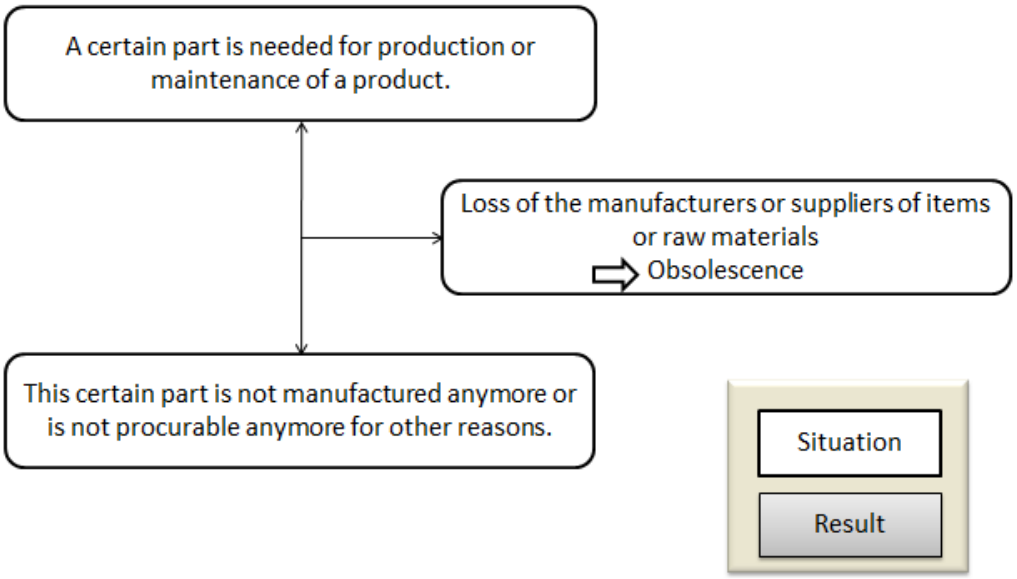


Figure 2-4 the appearance of Obsolescence Bartels et al. (2012)

In the scenarios analysed in the majority of research on obsolescence, obsolescence is referring to parts, processes, manufacturing technologies or suppliers becoming obsolete. Either a part can no longer be sourced, or a supplier has discontinued a service. In large commercial aircraft manufacture, this is rarely the case. Usually partnerships are negotiated well in advance with suppliers and support services. Unless the OEM no longer requires the part or service then it is unlikely to be discontinued due to the lucrative nature of a

consistent income stream for the supplier. Obsolescence from an industry leading manufacturer is not so much that there is no access to a resource, it is that a process, part or technology has been surpassed by newer processes and its continued use presents competitors with an opportunity to gain an advantage. An example can be demonstrated with the increase in production rates. If the manufacturing technology reaches its maximum capacity then that existing technology is limiting the progression of the company. A case can be made to duplicate technology; however, as the aircraft production life lasts in the region of decades, it is likely that the technology originally implemented is no longer the state of the art, and other commercial products are likely to have been developed. Therefore duplicating technology, although risk averse, is very likely to put the company at risk of falling behind its competitors. This kind of obsolescence is classified as *Functionality Improvement Dominated Obsolescence* (FIDO) by Bartels et al. (2012). It is defined as the evolution of products or processes in order to maintain market share.

Hitt and Schmidt (1998) attempted to illustrate the impact of obsolescence by mapping its impact upon future costs. The exercise is designed to support decision makers of investment decisions. They show that in the context of military equipment and systems, the cost of future obsolescence is higher than the cost of investment.

This can be considered as technology obsolescence despite the fact that the technology is still commercially available. There is also another issue to be taken into account. At initial aircraft design stage the manufacturing processes and

technologies are also being defined. The risk is that shifts to design will upset manufacturing optimisation drives.

In a manufacturing environment, when determining where investments should be made, management will typically ask two questions (Sandborn, 2007):

- Has a serious event occurred in the field that is causing this reaction? For example, an accident or common product defects.
- What future impact will be caused if this problem is not addressed?

As a result of this difficult scenario which engineers are typically unfamiliar with, obsolescence management remains a largely reactive activity.

Bloch (2007) discusses the categorisation of obsolescence and identifies this particular type of obsolescence. He mentions the work carried out by W.E.G Salter (1966) in which he provided an analysis on how technical process comes out through capital acquisition. He begins his analysis by identifying that at any time, with the constant establishment of new knowledge there is a spectrum of classifications within any manufacturing business. These range from processes that are up to date best practice to obsolete. Thus Salter (1966) defines obsolescence as when processes reach a stage where they can be profitably replaced.

Josais et al. (2009) also identified that in certain industries, such as aerospace and defence, the risk of part or process obsolescence is prominent due to the many instances where bespoke technology is implemented. As discussed, the lucrative nature of these industries prevents suppliers from halting the provision of these technologies even if they have been superseded. The authors recommend a proactive approach in mitigating the risk of obsolescence. They present a

regression model with multiple variables for forecasting obsolescence. The work is directed at the electronics industry but elements of it are also relevant to this scenario. The main difference is that unlike the electronics industry, there are a limited number of providers of aerospace capable manufacturing and assembly technology. The task of monitoring obsolescence risk isn't as great, but is overshadowed by the task of proving and implementing new technology and processes in the aerospace environment. A consistent benchmarking approach might be more suited to this task. Sandborn (2007) also discusses a similar proposal with regards to product components. He addresses the issue by including obsolescence consideration in the design stage and thus carrying out an obsolescence forecasting exercise.

2.4.1 Responding to obsolescence

Condra (1999) looked at how to deal with component obsolescence of electronic parts in aircraft. He identified that in the past, aircraft manufacturers didn't consider electronic component obsolescence a problem due to the defence sector making up 25% of the market share in electronic component development. The assumption was the component designs will remain stable for a long time. This is mirrored in the context of manufacturing. Such is the nature of aerospace assembly that suppliers to aerospace industry are required to dedicate large amounts of their resource towards that industry. However, in the solid state electronics sector, digitalisation of society meant that similar calibre components were no longer just required for military and aerospace applications and a host of new suppliers entered the market. This competition has led to shortening of component life due to innovation. Similarly, only a limited number of suppliers had the knowledge and resource to dedicate towards the requirements of aircraft

manufacture. However, the constant development of manufacturing and assembly technology has meant that suppliers that were traditionally only involved in other industries are able to diversify as development of their equipment starts to meet aircraft manufacturing requirements. This can be observed by the recent implementation of robotic manipulator arms on areas usually reserved for either manual or Cartesian monument tooling (Landau, 2016). The response in the solid electronic component sector was to consider three aspects:

- How to anticipate component obsolescence
- How to react to component obsolescence
- How to reduce the risk of component obsolescence.

The first of these points has been discussed already. The second point is addressed in a way that is not relevant to the type of obsolescence being discussed in this research. Most interesting for this research is the third point. The author suggests that the industry is required to move towards changing their design to accommodate the supporting industry as opposed to purely relying on suppliers to meet its requirements. If this suggestion is implemented in the realm of assembly and manufacturing than it would lead to the relaxation of accuracy and tolerance requirements for example. Such requirements are put in place by necessity in order to meet safety and performance criteria. This opens another strand of obsolescence and this is the obsolescence of analysis techniques. The question becomes how can the manufacturer realise when to take advantage of improved analysis techniques that can potentially lead to relaxed assembly and manufacturing requirements?

2.5 KNOWLEDGE MANAGEMENT

Zheng and Terpenny (2013) identify that one of the main challenges in obsolescence management is the integration of various types of knowledge. In any large multinational organisation with large numbers of work streams and many different sites, knowledge integration is a challenging task and even more so when discussing obsolescence of technology. For example, in the case of a large aerospace manufacturer such as is being discussed here, there is a multitude of plants all dealing with assembly. Traditional aircraft assembly of metallic aircraft mainly involves locating parts together, drilling holes and attaching those parts together through bolting. These similar activities are taking place over a number of countries and through a number of languages across many different plants.

Siemieniuch and Sinclair (1999) list the following in emerging best practice techniques for organisational aspects of knowledge lifecycle:

- Lead from the top. This requires a senior manager to practice a culture of quality and excellence in all aspects of company business not just its products.
- Communication of the vision of Quality and Excellence. This is the consistent communication by direct means and through action of the company direction from a learning and quality point of view. This is to all stakeholders including internal employees and external suppliers.
- Learn by Doing. This is the promotion of tacit knowledge development by absorbing the small risk of failure that this approach will yield. It is believed that the wider benefit outweighs the potential failure.

- Development of robust process models for change management. This is also related to Leading from the top, in that Knowledge that is generated is implemented. If generated knowledge is disregarded the company is in danger of becoming stagnant from progress point of view but also the company will promote a culture of change resistance and risk aversion.
- Access to Training.

These factors cater for both knowledge creation and knowledge sharing. However, although all the stated factors are relevant, there is no mention of the best practice in implementing them. Processes or specifications that facilitate these aspects of knowledge management would likely result in stronger knowledge care. Most interesting for this research is knowledge sharing. Knowledge creation is a consistent factor, to varying degrees of success, in any organisation developing new products. The challenge, as mentioned, is distributing that knowledge effectively. Davenport and Prusak (1998) mention that knowledge sharing is critical to a firms success as it leads to faster knowledge deployment. Al-Alawi et al. (2007) carried out research to identify positive contributors for successful knowledge sharing. They identified the following factors as being the most relevant:

- Trust between co-workers
- Communication between staff
- Information systems
- Reward system
- Organisation structure

Riege (2005) carried out an extensive literature review on identifying the barriers to knowledge sharing. He categorises the barriers into three sections. The first are individual barriers and these include the following:

- Lack of time
- Job security fear if key knowledge is no longer personal
- Limited awareness on value of knowledge sharing
- Company blame culture
- Inefficiency in formal capture of knowledge such as report generation and referencing
- Social and cultural differences between employees such as nationality, language, age, sex and education level.
- Lack of trust between employees.

The second category identified by Riege (2005) were organisational barriers and these included the following:

- Unclear or ineffective knowledge management strategy and guidelines.
- Lack of leadership example.
- Shortage of formal and informal forums to share knowledge
- Lack of transparent rewards for knowledge sharing
- Barriers within corporate organisational structure
- Ineffective dissemination methods
- Resistance to external knowledge
- Physical barriers such as office layout or even plant locations

The final category was technology barriers:

- Lack of commonality in Information Technology hardware and software.
- Lack of technical support for integrated knowledge management IT
- Unrealistic expectations of technology
- Lack of training on technology systems
- Lack of communication of advantages of technology implementation such as Knowledge management software.

The factors that contribute to barriers in knowledge sharing are highly relevant in DFA and obsolescence management. In a large manufacturing business such as is being discussed issues such as time constrains, physical and cultural constraints are highly relevant. However, the reluctance to engage in obsolescence assessment goes beyond access to knowledge. Whilst each manufacturing site might be similar in a general sense, the knowledge that is generated usually has key differences that stop direct application in other plants and thus it is dismissed. A knowledge classification system would be key in providing a service where similar knowledge can be identified.
Controlling knowledge development and sharing under these circumstances is very difficult.

Zheng and Terpenny (2013) attempted to solve this problem through the introduction of a hybrid ontology approach. Ontologies are typically defined as a set of views that provide a unified conceptual view of the underlying data (Mecca et al., 2015). The need for an effective knowledge classification method to mine through the large amounts of unstructured knowledge generated in natural language is critical in large organisations (Sanchez-Pi, et al., 2015). Ontologies

provide named entities and relationships between them, an intermediate categorization step requires matching terms to ontological entities.

Zheng and Terpenny (2013) developed global ontologies that provide a shared language for information. These are then linked with local ontologies that provide structures for local data sources that provide information about obsolescence in those local areas.

Chen et al. (2009) developed a framework for integrating product knowledge lifecycle into enterprise organisations. The method developed uses ontologies to classify generated knowledge in order to create ease of access for stake holders within the enterprise. The frameworks for knowledge generation and classification are shown in Figure 2-5, the framework to integrate into the enterprise is shown in Figure 2-6. Interestingly for this research, this ontology based method highlights that one of the main factors in this method are the following three factors:

- Ontology-based knowledge mapping
- Ontology-based knowledge merging
- Ontology-based knowledge searching

These three aspects are of particular importance in overcoming the challenges presented at the beginning of any DFA investigation or even any engineering investigation and this researcher believes will be key in developing a model for integration of knowledge into project investigation.

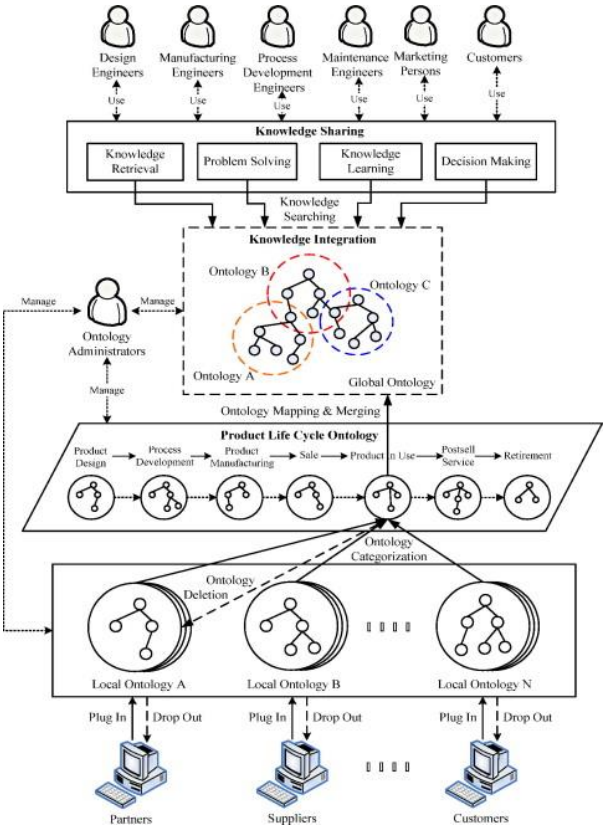


Figure 2-5 Ontology-based framework for integrating product lifecycle knowledge. (Chen, Chen and Chu, 2009)

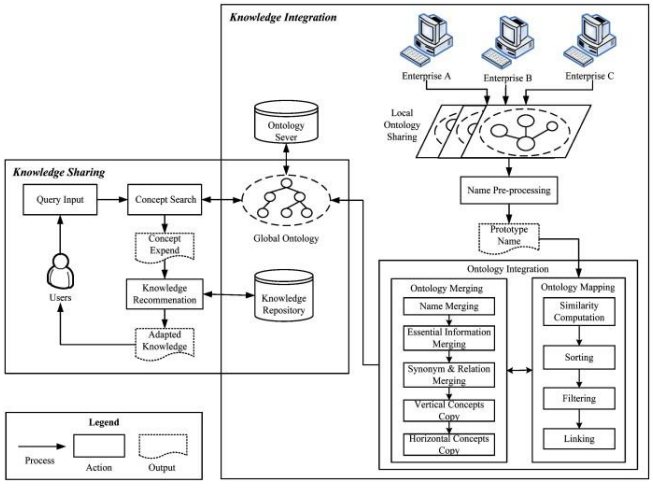


Figure 2-6 Integration and sharing process for ontology-based product lifecycle knowledge. (Chen, Chen and Chu, 2009)

The detail of these ontologies is key in grouping together knowledge categories and thus the effectiveness of the classification system is only as powerful as the initial requirements. An example of this is a process that involves a robot arm and drilling end effector. If a simplistic classification for the development of this knowledge is the use of the robot and the requirement for particular drilling parameters then it would appear to be related to all drilling processes and all robot processes. If however, it is further broken down, and the direction of drilling, the challenges of drilling in that area, the specific nature of the product in that area are all captured, than this would become particularly useful at DFA stage as this enables the development team to gain further insights into the relationships between varying processes. This method offers an interesting platform to build upon however, carrying out classification to a high level goes against the objective of this research, which was to develop a method to offer rapid insight. No doubt, this ontological approach would benefit any large organisation in the long term, but it would take great effort to implement and thus goes against the target of this research.

2.6 PRODUCT LIFECYCLE MANAGEMENT

A closely associated issue with DFA, obsolescence and knowledge management is lifecycle management. In a DFA domain the life cycle categorisation of a product will play a significant part in manufacturing and assembly criteria.

Stark (2015) defines product lifecycle management (PLM) as:

"The activity managing a company's products all the way across their lifecycles in the most effective way."

He states that the goal of PLM is to allow a company to take control of its products. Implementation of effective PLM means that an effective product

strategy is defined. This can lead to both increased revenues and reduced costs. An example of how DFA and PLM interface is in comparing the automotive and aerospace manufacturing sectors. Automotive factories are typically heavily automated whilst aircraft manufacturing, although has certain aspects that are automated also has large elements of manual assembly. This is the most cost effective solution for both scenarios. In the automotive sectors, the product manufacturing rate can be significantly higher than aircraft production and thus justification can be made for the integration of expensive automated systems. The lower rate of production in aircraft manufacture mean that incorporating some elements of manual assembly is the most cost effective method of achieving targets. This is a simplistic view and there are other factors that influence these decisions, however, it offers an insight as to how PLM strategy implementation is effective.

However, much like DFA practice, there are aircraft that entered into production before the widespread adoption of PLM strategy. Thus on legacy aircraft, it can be observed that no contingency has been made in the design of the product and manufacturing infrastructure for the advances in manufacturing technology. A strategy to realise this has the potential to offer significant development and capital expenditure savings.

2.7 COMPLEXITY

Another part of the DFA process that is particularly significant to large volume assembly is complexity analysis. Defining complexity is difficult. Each methodology will define complexity according to the realm it functions within. Thus there are a variety of definitions for complexity (Park and Kremer, 2015). The context in this case is both design and manufacturing. Within that there are

two forms of complexity (Park and Kremer, 2015); Static complexity and dynamic complexity. Static complexity is the inherent complexity in the system if everything were to function as intended. Dynamic complexity is the complexity introduced due to uncertainty in the system, such as machine failure.

Zeltzer (2012) defines complexity as follows:

"*Complexity is the sum of all aspects and elements that makes a task or a set of tasks mentally difficult, error-prone, requiring thinking and vigilance and inducing stress.*"

Through a series of workshops in the automotive industry the following complexity drivers were produced relating to manufacturing:

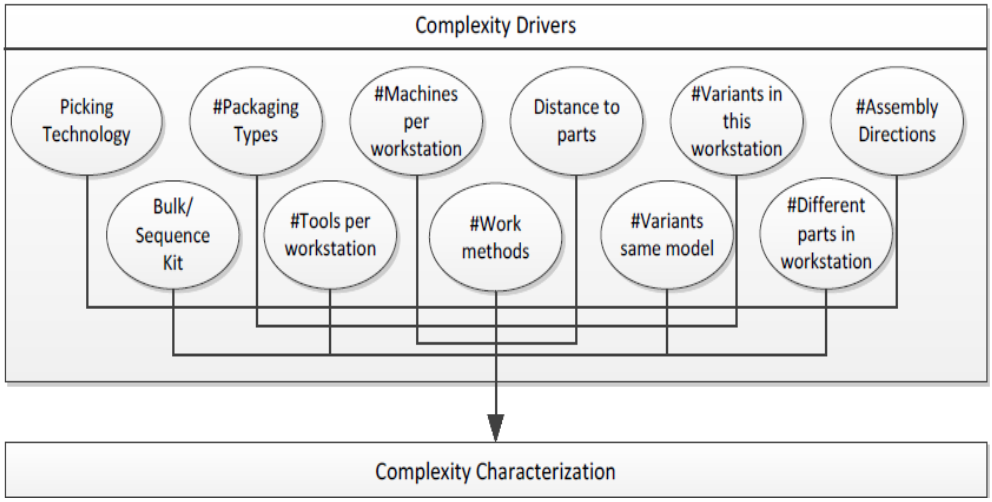


Figure 2-7 Zeltzer (2012). Complexity Factors

The complexity drivers shown in Figure 2-7 are not all directly applicable to large volume component assembly. Some of the drivers are largely associated with small components, such as picking technology, packaging types and distance to parts whilst others such as variant models, variants in this work station and

bulk/sequence kit are not applicable. Also, of these drivers there is no account for the components themselves.

Similarly, Park and Kremer (2015) carry out an analysis of the impact of dynamic and static complexity on manufacturing performance. Their analysis was aimed at assisting the decision making process in deciding a manufacturing strategy (stock to sell or make to order).

Calinescu et al. (1998) highlights the following factors that influence complexity:

- The product structure; this is factors such as the number of parts, the cycle times, the nature of the subassemblies and the sequence of processes and requirements to produce it.
- The structure of the shop or the plant; this involves aspects such as the layout of the factory, maintenance tasks, set-up times, idle times and even performance measures.
- The planning and scheduling functions; This encompasses three elements: The planning and scheduling strategies, the documents used for planning and the decision making process.
- The Information Flow; this is how internal departments communicate with each other and how separate business stakeholders communicate with the business.
- Dynamism, variability and uncertainty of the environment. This encompasses quality issues, absenteeism, unreliability, customer changes and market risk.

In a broader analysis, Fisk (2004) looks at engineering complexity as a whole. He argues against the notion that the higher the complexity of an engineering system

the more likely it is to be at risk of collapse. He argues that it is inevitable that complexity within engineering systems will increase as capability of those systems increases. However, he says that there is a difference between extensive complexity and intensive complexity. Extensive complexity is that complexity that is introduced into the system due to mitigation. For example, as a system or product is developed, mitigating engineering solutions are bolted on. These are unanticipated and this is the type of complexity that leads to instability. Intensive complexity is the complexity of a system that is planned for in recognition of the capability of the system. Simple systems cannot achieve higher capability, but in an intensive complexity environment, the inherent complexity is planned for and mitigated against in the overall design of the system. He also highlights that shocks to the manufacturing system are what really define its stability. Without a major shock there may be venerable aspects of the manufacturing system that have not been exposed. His concluding advice is that complexity is not something that needs to be avoided rather it is something that needs to be respected. However, he offers no indication, even on a philosophical level as to how that respect should manifest.

Complexity is a far reaching topic and can range from analysis of business organisation complexity to engineering complexity. Whilst not directly relevant there are parallels that can be drawn from complexity analysis outside of manufacturing.

In the realm of project management, Baccarini (1996), carries out an extensive literature review on the impact of project complexity specifically in the realm of construction projects. There is a clear correlation between management effort

and project complexity. He states that the following impacts are affected with increasing project complexity:

- Determination of planning effort, co-ordination requirements and control requirements
- Complexity hinders the clear definition of goals and objectives for major projects.
- Complexity is a critical criteria in organisational set up.
- Complexity influences the selection of project inputs.
- Complexity is used as a criteria in procurement selection.
- Complexity affects the project objectives from a time, cost and quality perspective. Generally speaking the more complex the project the more time and cost required to achieve a targeted level of quality.

All of these points are relatable to manufacturing and product complexity. Planning effort even when a product is in a steady state of production requires significantly more effort if is around a complex manufacturing system and product. Further, a complex product or manufacturing system loses sight of the fact that the aim of most businesses is to seek a profit. This can be lost in the face of a complex product designed to achieve performance objective. Also, the more complex a product or manufacturing system is the more difficult it is to be competitive in the area of procurement. This is because as the complexity increases the number of available suppliers decreases. This is true for both product complexity and manufacturing system complexity. For example, a requirement that a part is made out of an expensive and difficult to machine material such as titanium, immediately reduces the number of manufacturers that can provide that service. Similarly, a requirement for a robot to hold a high

repeatable accuracy not only reduces the number of suppliers able to achieve such a target, but also increases the cost drastically because of the bespoke requirement of the system.

The majority of the research regarding complexity relates to general complex systems. Of the many definitions that have been derived with regards to complex systems the two that are perhaps best regarded are the Shannon Information theory and Kolmogorov complexity (Lui et al., 2015.)

The complexity of a system is often measured through the amount of information produced by the system. When these outputs are measured they are encoded into a series of strings. These strings are essentially the message or the result that the system is designed to produce. The complexity is thus assessed based on the information contained within these strings.

The Kolmogrov method of assessing complexity is to measure the consistency in the string output. This means assessing how regularly the same result is produced using the same system and inputs. The Shannon Information method proposes a mathematical framework that relates success of achieving system design intent. This theory measures the probability of achieving that design intent. The majority of complexity assessment theory are variations on these two pieces of research.

2.8 COST ESTIMATION

Cost estimation is defined by the Association for the Advancement of Cost Engineering (AACE, 1990) as follows:

"The determination of quantity and the predicting or forecasting, within a defined scope, of the costs required to construct and equip a facility, to manufacture goods, or to finish a service."

Romero (2011) discusses a number of challenges when creating accurate cost estimates:

- Access to reliable data
- Experienced cost engineers
- Lack of definition in risk assessment
- Ambiguous assumptions
- Stability of company forecast
- Time constrains in creating estimates.

Niazi (2006) illustrates the different strands of cost estimation techniques in Figure 2-8 .

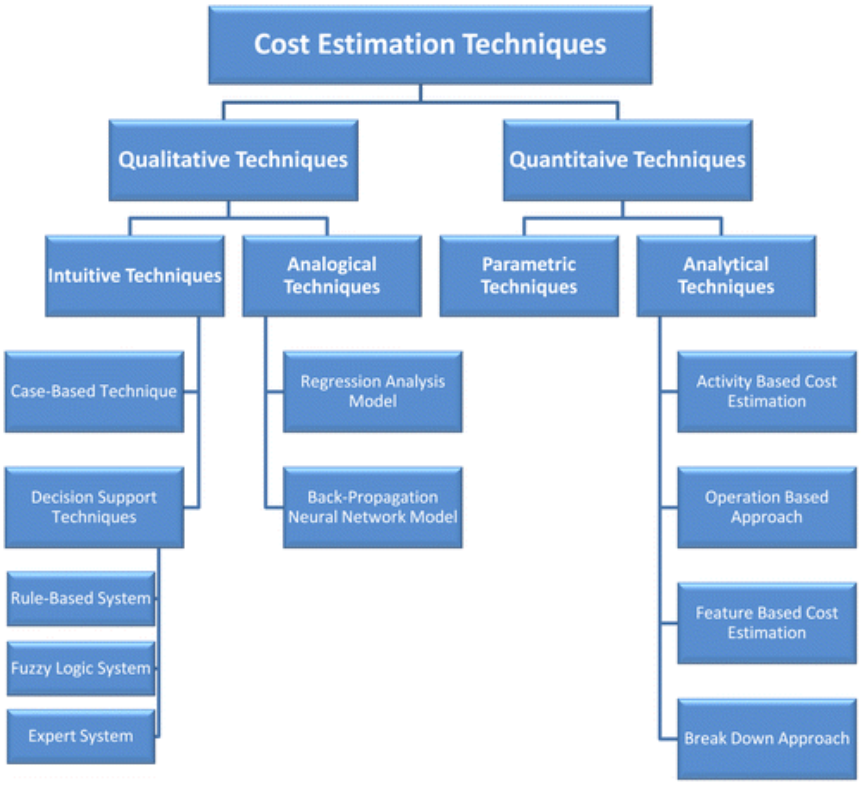


Figure 2-8 Niazi (2006) Cost Estimation Techniques

This is summarised by Hueber et al. (2016) into three basic methods, demonstrated in Figure 2-9.

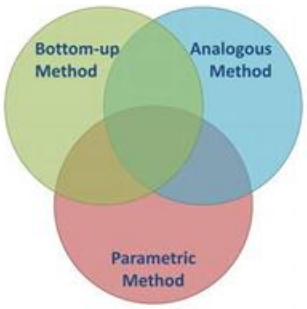


Figure 2-9 Adapted from Heuber et al. (2016), Methodologies in cost estimation.

Parametric

Stewart et al. (1995) defines the parametric approach as follows:

"The process of estimating cost by using mathematical equations that relate cost

to one or more physical or performance variables associated with the item being estimated"

This technique aims to use historical data to identify consistencies that can be used to form Cost Estimating Relationships (CER). An assumption of the technique is that factors that currently influence product cost will continue to do so in the future. The technique relies heavily on the quality of the data it uses. For the purposes of a forward looking manufacturing system aiming to implement currently immature assembly technology it can be useful. This is provided that assembly process or material being operated on is an adjustment of a previous process. For example, in the case of aircraft assembly implementing a new drilling application on a robotic arm is likely to face similar cost challenges to previous applications.

Bottom up costing

This is a method that is generally applied when many of the project components are known and the project scope has been defined. Cost estimations are carried out on the lowest level of detail by experienced engineers. Usually, work packages are defined into sub work packages until the project is comprehensively planned and cost estimation takes place on the lowest denominator defined. (Trivailo et al., 2012). The value of this approach in planning for immature technology is limited. There is only a limited level of definition for a potential future project and even an experienced engineer will only be able to form vague estimates.

Analogous Estimation

This is a method also known as case based reasoning (Roy, 2003). In this method, it is assumed that similarities can be drawn for each new development project with existing projects and is evolved by factoring in new parameters. This method also relies heavily on the quality of the data available. In a manufacturing development project, this method is particularly relevant. Specifically in aerospace assembly domain, decision makers are risk averse. Therefore assembly optimisation development projects are usually incremental and are thus related to previous projects.

The analogous method is the method that is most suitable to the concept and development stage. This is illustrated by Jones (2014), in Figure 2-10.

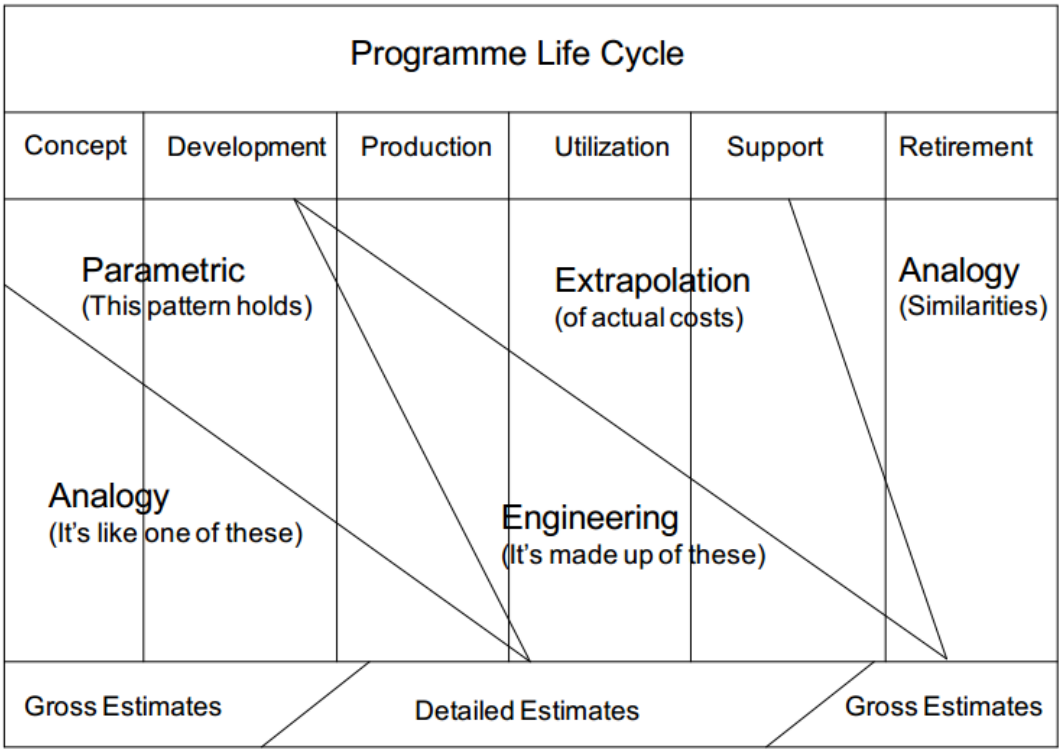


Figure 2-10 Showing the most suitable cost estimation techniques for different stages of the product life cycle

Although Parametric and Analogous are both listed as being suitable for concept and development, parametric favours a higher maturity of development. In the kind of development projects being considered in this research projects have not been explored yet and maturity is only assessed through benchmarking across the industry.

Tool Sets

The cost estimation techniques that have been mentioned are those specific to technology development. A number of tool sets have been developed based on these techniques. They are as follows:

COCOMO

The Constructive Cost Model (COCOMO) is a parametric algorithm. The model was built based on a historical data set of 63 projects. It is based on an equation that estimates effort, development time, and the maintenance effort (Sachan et al., 2016). This tool set has not been adapted to estimating advanced manufacturing technology applications (Jones, 2014).

COSYSMO

The Constructive Systems Engineering Cost Model (COSYSMO) was based on COCOMO methodology and tailored for estimation of system engineering. This system was developed by Valerdi (2005), but similar to the COCOMO method, the system has not been applied for manufacturing technology development (Jones, 2014).

Trueplanner (Price Systems)

Trueplanner by Price systems is also a tool that relies on the parametric method. It includes several cost models such as True-H for hardware cost estimation and True-S for software estimation. Both are derived from cost estimation relationships that are derived from historical data. The models can be calibrated for specific applications and are potentially useful for the justification of future investment of current low maturity technology. (Jones, 2014)

SEER by Galorath Incorporated

The Systems Evaluation and Estimation of Resources is a cost model developed by Galorath. It is suited to estimating the initial stages of development. It incorporates aspects of both analogous and parametric cost estimation methods. It carries out an initial analogy stage followed by a second parametric and compares the results together. (Jones, 2014)

P-Beat

The Process Based Economic Analysis Tool (P-Beat) developed by Boeing and NASA (Schankman and Reynolds, 2010). This tool also combines parametric and analogous methods. The model establishes cost estimation relationships that are driven by technology maturity, design maturity, resource capability and software and hardware complexity.

2.9 Gaps in literature and research

The literature review highlights that there are gaps in the field of DFA application in aircraft manufacturing. A notable gap is that of redesign for assembly. This takes significant prominence in such an industry due to the length of the life of the

product spanning several decades. As has been discussed, traditional DFA methods are not capable of addressing the nuances of optimising a highly complex product for manufacturability over the course of this time scale. Research into addressing this gap is explored in Chapter 4.

Traditional DFA does not acknowledge in service product optimisation and even when it does, there is no accommodation for aerospace applications. This leads onto the next gap identified. This is that of macro analysis for input into DFA during product development.

As traditional DFA isn't able to provide beneficial outcomes in both redesign and product development, a method is required that is capable. In order to do this in a manner that encompasses every aspect of production and the manufacturing system. This analysis needs to take place on a macro scale and encompass the manufacturing system, not just the product. Traditional DFA methods only consider the product or the manufacturing system in isolation. Research into addressing this gap is explored in Chapter 5.

A number of methods were identified that could carry out assessments of specific areas with a particular factor that would act as the basis of the analysis, such as accessibility (Hsu and Lin, 2002). However there was no method that analysed a number of factors that would all contribute towards increasing ease of assembly or manufacturability.

The final gap identified and addressed within this research was that there was no DFA method that considered the development cycle of both the manufacturing technology and the product. Previous research addressed DFA from a product perspective. There is no view as to which technology was planned to be used to carry out assembly and how that technology was likely to change in the future. Throughout the course of the literature review there appeared to be very limited

research carried out in considering manufacturing and assembly technology future development during the Design for Assembly process. This researcher considered this a vital area particularly in an industry where the assembly technology is typically highly specialised. For such a specialised technology stream, future technology development, whether that be company strategy or industry road mapping, should be considered at product development stage so that the manufacturing system does not suffer from competitive obsolescence. Research into addressing this gap is explored in Chapter 6.

3. METHODOLOGY

3.1 INTRODUCTION

Leedy (1997) highlights a number of criteria when planning a research project. These criteria are factors that are common to all research and serve as guidelines during the planning stage. They are as follows:

- Universality; this is that the research should be able to be carried out by any other person.
- Replication; the research should be repeatable by any common person with resulting similar outcomes.
- Control; the same experiment should be conducted a number of times under the same condition to limit anomalous bias.
- Measurement; the results of the research should be subjected to measurement.

The four aspects of planning presented above are used throughout this research. The research target is to produce methods and tools that can be applied to DFA. The context of the research is within commercial aircraft manufacture. The methods that are presented in this research, whilst having been developed using this context and the available data from this field, are applicable universally and can be transferred away from the aerospace industry. The repeatability of the research is demonstrated through the development of tools to facilitate the proposed methods and also in demonstrating the application of those methods when a tool is not necessary. The research controls in the case of this research is the data provided by the industrial partner. This is industrial data amassed over several decades and is thus considered reliable. Measurement is carried out

throughout the research through comparing results provided by the method with real world decisions carried out by the industrial partner.

3.2 SCOPE

3.2.1 Wing box assembly – description of wing box assembly

The methods and tools developed in this research have been implemented on wing box assembly. To clarify, this is the assembly of the structure of the wing before the installation of systems and moveable's. An exploded view of the wing box structure is shown in Figure 3-1.

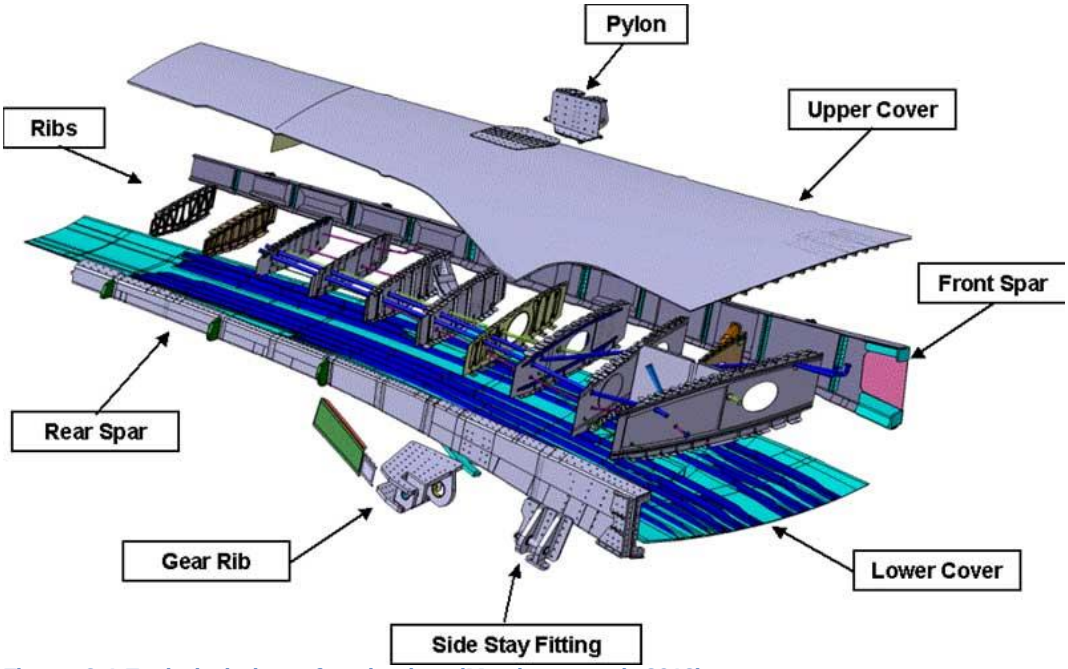


Figure 3-1 Exploded view of a wing box (Muelaner et al., 2013)

The wing box is comprised of the following major components:

- Wing Panels/Skins: These are the large thin structures that cover both sides of the wing box. They are typically referred to as either the Top skin or the Bottom skin.
- Ribs: These are the structures that provide the structure to the wing and make up the fuel tanks.

- Spars: These are the long components that are assembled with the leading and trailing edges. They come as preassembled parts and are the first components to be installed into the main assembly fixtures. The front and rear spar are attached to the fixture datum flags.
- Pylon structures: These are the titanium components that the Pylon attaches to. The Pylon is the component that carries the engines.
- Gear Rib structures: These are also titanium components that facilitate the attachment of the Landing Gear assemblies.

The assembly method is represented in the flow chart in Figure 3-2

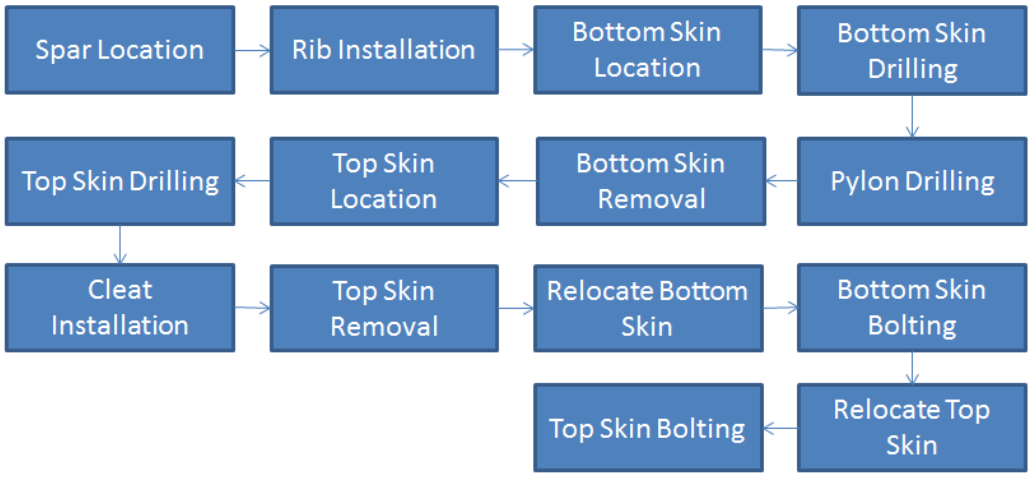


Figure 3-2 Flow Chart of the processes involved in wing box assembly

1. *Spar location:* This is the location of the preassembled spars with the associated leading and trailing edges onto the main assembly fixture. These spars are positioned according to tooling flags on the main assembly fixtures and provide the main point of reference for the location of other parts during assembly. The main assembly fixtures are monument steel structures that are designed to be datum points through tooling flags as the structure of the wing box is assembled. The spars are located

through their hinge lines. These hinge lines are what the moveable's, such as flaps and ailerons are attached to after wing box assembly. Thus it is important that these hinge lines are held to a tight tolerance as they are designed to fit interchangeable components.

2. *Rib Installation:* Ribs are located in between the spars using dedicated tooling and are then drilled and bolted into the corresponding rib posts located on the spar. Two types of tooling are used. The first are drill jigs that assist in positioning the ribs correctly and the second are support structures named "strong backs" that give added stiffness to the ribs during assembly. This is to accommodate the forces that are transferred through the wing panel assembly stage and also to maintain the box shape without all components attached.
3. *Bottom Skin Location:* The pre-assembled bottom skin is located and wrapped around the ribs using cranes and clamps. It is positioned according to an overhang distance that corresponds to the rear spar. The location of the bottom skin is carried out using overhead cranes with dedicated skilled operators manoeuvring these large components into position.
4. *Bottom Skin Drilling:* Specific drilling equipment is used to carry out drilling on the surface of the Bottom skin and into the spars and ribs. The main assembly fixtures provide several levels of staging for access to all areas of the bottom skin. Whilst there is enough space for the operators to manoeuvre and position themselves, there is limited space for any large industrial machinery.
5. *Pylon Drilling:* Specific drilling equipment is used to assemble components related to the pylon. The titanium material of the pylon area requires large

clamping forces to maintain the assembly in a characteristic that allows effective drilling.

6. *Bottom Skin Removal:* The bottom skin is removed, cleaned and debbured and then stored awaiting reassembly.
7. *Top Skin Location:* The pre-assembled Top skin is located and wrapped around the ribs using cranes and clamps. It is positioned according to an overhand distance that corresponds to the rear spar. Similar to the Bottom skin, it is carried using over head cranes operated by specialist operators.
8. *Top Skin Drilling:* Specific drilling equipment is used to carry out drilling on the surface of the Top skin and into the spars and ribs.
9. *Cleat Installation:* Butterfly brackets are installed to add support between the skin stringers and ribs. This process happens inside the wing box and each bracket requires 4 holes, 2 on every interface. The brackets are removed after drilling for cleaning and deburring.
10. *Top Skin Removal:* Top skin is removed, cleaned and deburred.
11. *Relocate Bottom Skin:* The Bottom skin is reassembled onto the wing box skeleton matching previously drilled holes. Again, this is carried out using overhead cranes. Relocation of skin panels is particularly challenging due to their flexible nature and that their form is not controlled during handling and storage.
12. *Bottom Skin Bolting:* Bolts are installed and sealed between the Bottom skin, spar and rib components. It is important to note that access is required from both sides in this area.
13. *Relocate Top Skin and Bolting:* The Top skin is relocated in two parts. The first part is located and bolted using the gap left by the second part of the wing skin for access into the box to carry out torqueing operations. The

second part is then located and bolted using the man holes in the bottom skin for access into the wing box to carry out torqueing operations. The requirement for in tank work is challenging and requires operators of suitable size and flexibility. Further, it poses ergonomic, health and safety challenges.

3.3 METHODOLOGY STRATEGY

3.3.1 General Methodology Strategy

The strategy for methodology and tool development in this research will contain two main aspects. These are as follows:

- The reliance on legacy data to influence future decisions
- The consultation of industrial knowledge to provide steering.

In this way, methods are developed based on industrial experience. As this research is industrially focused this provides a strong platform on which to build relevant methods.

3.3.2 Redesign

This research area covers DFA applications for products that are already in production and are likely to remain in production for the foreseeable future. The main advantage in this field is that there is a large amount of readily available data that can be explored. As such this forms the initial foundation in developing a method to achieve the aims of this research. The method will follow the steps listed below:

1. Data Acquisition
2. Analysis
3. Idea Generation

4. Selection and Approval
5. Implementation

3.3.3 Macro analysis and Complexity

Whilst the first part of the research is aimed at dealing with DFA application for existing products, the second branch of this research aims at the broader topic of macro analysis. Traditional DFA methods assess a product with specific features in mind. There is no mapping of how a particular assembly or part of an assembly will affect the overall manufacturing system. It has already been mentioned that the real aim of any DFA analysis is cost reduction over the life time of a product. Introducing manufacturing easement through design in one stage that will adversely affect the rest of the manufacturing system is something to be avoided. The aim of this part of the research is to develop a method that can produce a macro analysis of the manufacturing or production system that can relate to cost indicators such as time and quality.. The following steps are the intended steps taken to develop a methodology and toolsets for this branch of the research.

1. Define element of macro analysis for implementation
2. Define features of element
3. Identify contributing factors
4. Measure those factors
5. Create Macro Analysis
6. Introduce Controls
7. Draw Conclusions

For each industrial scenario the key element that can lead to a macro analysis may differ. As such, the first step in any macro type analyse is defining that

element. In this research this was defined as Complexity. Chapter 5 goes into more detail as to why this particular element was selected.

3.3.4 Future Planning and Shared Platform approach

The final branch of this research is in the field of forward planning for DFA applications. As has been mentioned, it was found that there was a gap in the research in the consideration of product and technology as a single entity. This is particularly poignant for aerospace assembly where traditionally bespoke technology is required to achieve stringent accuracy requirements of large volume assemblies.

The method development strategy for this strand of research was to consider the process independently of its technology. The following steps are proposed:

- Process characteristic analysis
- Process classification
- Cost reduction target prioritisation
- Mediation between technology and design to achieve best cost outcome.

The key to this method is identification of process characteristics that are independent of the process outcome for product and technology manipulation. This is the simultaneous development of the product to make allowances for profitable technology and also the development of the assembly technology to make allowances for the product. In this way, investment can be targeted at achieving the best future cost outcome over the life time of the product.

3.3.5 Measuring Methodology Success

To measure the success of the proposed methods and tools a multi part assessment criterion is used. Measuring the success of these methodologies is partly subjective and partly analytical. It is difficult to assess those methodologies that deal with DFA for future and legacy products as the results that they produce haven't been realised. However, comparisons can be drawn with legacy activities and for this reason some of the methods and tools presented in this research have been practically applied using legacy data. A brief summary of how each method is assessed is discussed as follows:

- Redesign; this is perhaps the most straight forward to assess. Existing data is used to carry out the analysis and thus the outcomes of the proposed method can be directly compared with business decisions.
- Macro analysis and complexity; although this method can be applied for future product development and existing products, existing legacy data is used to demonstrate the concept. The success of the conclusions that are drawn from the analysis will be difficult to assess. Decisions made by the business, or problem areas identified by the business could offer some guidance as to the success of the tool, but definitive conclusions can only be achieved through the implementation of the ideas presented.
- Future Planning and Shared platform approach; this is the most difficult method to assess. The method is demonstrated through existing assembly processes. The success of the proposals put forward is subjective and can only be conclusively proven if implementation of the suggestions is adopted.

4. REDESIGN FOR ASSEMBLY

4.1 INTRODUCTION

In the realm of commercial aircraft manufacturers, product improvement has typically been carried out in pursuit of product optimisation with the intention of generating sales. As for optimising manufacturing and assembly, small to medium scale technology insertion has been the typical solution for enhancing the production system. Changes in design to create manufacturing easement have been difficult to achieve due to the challenge in demonstrating an attractive business case. The high cost of carrying out design changes and the potential for recertification costs is prohibitive. Also the reward for decreasing manufacturing costs is typically not comparable to the reward from sales and performance savings achieved through performance modifications. The success of the single aisle aircraft market is also a factor as manufacturers adopt a risk averse attitude so as not to compromise delivery of aircraft and thus lose market share.

As mentioned in Chapter 1, in more recent years, sales of these aircraft have been numerous and decreasing delivery lead time and cost reduction have become more prominent issues. Therefore, manufacturing and assembly system improvements are being demanded by the business and the introduction of design changes for assembly easement are viewed more favourably. Continuous product development teams are now encouraged to pursue them.

One of the aims of this research is to provide optimised methods and tools for DFA application in the commercial aerospace assembly field. Whilst DFA has predominantly been used during development, there is a requirement for a consistent parallel analysis on existing products. Indeed, legacy products make up the majority of Airbus or Boeing fleets and orders of those products continue to

rise. Thus it is prudent to develop methods and tools to increase the cost efficiency of those products.

This chapter begins by outlining the previous work that has been carried out specifically on Redesign for Assembly, it then goes onto discuss what the unique aspects for the specific scenario being addressed are. After identifying these, a methodology is proposed to address DFA in this area. A tool is also created to implement the methodology. The tool is demonstrated using the example of butterfly brackets that are installed on wing cover stringers to rib interfaces. The tool is then populated using many other processes and the results are compared against real business decisions to determine the effectiveness of the tool.

4.1.1 DFMA on a Wing box

Typically the first port of call when carrying out a DFMA assessment is the widely popular Boothroyd and Dewhurst method that has been mentioned in the literature. As such, a Boothroyd analysis is carried out below on a wing box.

	Is the Part required to move during operation relative to other parts	Does the part need to be a different material	Does the part need to be separate to enable assembly of other parts	Required as a separate part?
Top Skin	No	No	Yes	Yes
Bottom Skin	No	No	No	No
Ribs	No	No	No	No
Rear Spar	No	No	No	No
Front Spar	No	No	No	No
Pylon	No	Yes	No	Yes
Gear Rib	No	Yes	No	Yes

Table 4-1 Boothroyd and Dewhurst, DFMA analysis of a wingbox

This Boothroyd analysis is carried out on a wing box assembly before systems are installed. It indicates that a wing box should be a single component apart from the Upper cover (Top skin), the gear rib and the pylon. The reason the upper

cover is required to be separate is because access to the lower cover is required to carry out torqueing operations upon bolting. The upper cover requires similar access and this is why the lower cover has man holes designed in to facilitate this access. The pylon and gear rib are high load baring areas and as such they are manufactured from titanium. Thus this analysis points towards the idea that many of the components of a wingbox assembly should appear as a single component.

There are several options for such an arrangement. The first is to machine the wing box from a solid block of aluminium and then assemble the remaining parts. Or, perhaps, using modern technology this can be made either through co-layup using composite materials or using additive manufacturing. The first notion is impractical from a perspective of wasted material and cost aspect.
The net shape approach is theoretically more practical, however both those options are still far from mature technologies in that volume of component. The composite route is perhaps closer to maturity but extensive testing would still need to take place in order to develop confidence in implementing such a method in the typically risk averse commercial aircraft manufacture domain. The use of additive manufacturing for such a large component is currently not possible and is unknown when such a task would be feasible.
Thus the Boothroyd and Dewhurst method does not provide a positive approach when carrying out critical thinking on the manufacture and assembly of large volume structures.

4.1.2 Proposal

DFA methodology has traditionally focused on new products that are small in physical volume. The challenges in design for assembly of aircraft are different and can be summarised as follows:

- Large volume components.
- High tolerance assembly criteria (Positional accuracies of holes at 0.2 mm).
- Long life products.
- High capital monument technology and tooling already in place.
- Uncompromising delivery targets.
- Knowledge disconnect.

Large Volume components: Components require specialised tooling for lifting and handling. Accessibility is also an issue due to the components limited line of site. Operators are sometimes working on assemblies without having visual sight to all areas being affected. There are also times when the operator is required to do work inside closed boxes and cramped spaces. These aspects do not form part of the critical thinking in small volume assemblies.

High tolerance assembly criteria: Due to the large safety requirement for aircraft, assembly tolerances are high. Coupled with the large volume of aircraft this makes the costs of associated assembly technology high. This aspect is one of the advantages that can be gained through careful redesign analysis.

Long Life Products: This is the largest factor in creating assembly issues when competing against rivals. Although the processes that are in place are functional, in many instances there are likely to be superior options available. For example, new aircraft programs such as the Airbus A350 and the Boeing 787 are likely to have developed new assembly processes that may be backward compatible.

Similarly, the technology used during assembly has likely been superseded throughout the years.

High Capital Monument technologies: Expensive bespoke technology has already been invested in, such as high accuracy fixtures and bespoke monument automation. Also problematic is that datum structures for legacy products typically reference high accuracy fixtures.

Uncompromising Delivery Targets: There is a cultural reluctance to introduce any changes that may put the production system at risk of not meeting its immediate delivery targets. With performance improvements, this risk is offset by the estimated revenue generation. In the realm of production system improvement, as mentioned before, redesign for assembly, up until very recently, had been considered a major risk. Even technology insertion, which has been the predominant method of improving the production system, is carried out in a manner where only small scale step changes are introduced. Further to this, the introduction of new technology or processes would entail training and ramp up costs and delays that would be viewed unfavourably.

Knowledge Disconnect: Another interesting element contributing to a lack of redesign for assembly activity is knowledge on where to carry out projects. As mentioned, the business is interested in exploiting any opportunity to increase production rates and reduce costs. When continuous improvement teams attempt to identify areas or projects that would benefit from a redesign analysis they rely on information from production teams. This researcher carried an investigation with members from different production teams. They were asked what changes to

the product could yield an assembly improvement. Most suggestions were minor changes that would yield small savings that although not insignificant, would not justify the cost of design changes.

Thus it becomes apparent that a method for identifying where redesign activities can take place is needed on legacy products and production systems.

4.2 REDESIGN METHODOLOGY

A methodology is therefore proposed to carry out aspects of traditional DFMA methods but also account for its application on existing production systems. The method is designed to streamline the project selection process and is listed as follows:

1. Data Acquisition
2. Analysis
3. Idea Generation
4. Selection and Approval
5. Implementation

The methodology follows a linear flow. Structured Data gathering is the first step, followed by knowledge generation that leads to solution generation and implementation. The first two stages of the flow are the creation of knowledge. After knowledge is generated, solution generation becomes the target. The aim of this method is not to generate solutions, rather the aim is to highlight where Redesign for Assembly projects may be profitable. Corbett and Crookall (1986) highlight that rigid solution engineering techniques are not the most effective way of producing engineering results. Rather, engineers should be allowed to apply

their own ingenuity and creativity in finding solutions. This is the approach adopted by this methodology.

Whilst engineers should perhaps typically be left to create solutions through uncontrolled innovation, the selection and approval process inherently plays a critical part in the project progression. Frustratingly, it is not always the optimal solutions that are selected for implementation due to circumstantial prohibitors such as simultaneous projects, company direction or even negative company politics.

The methodology is summarised in Figure 4-1.

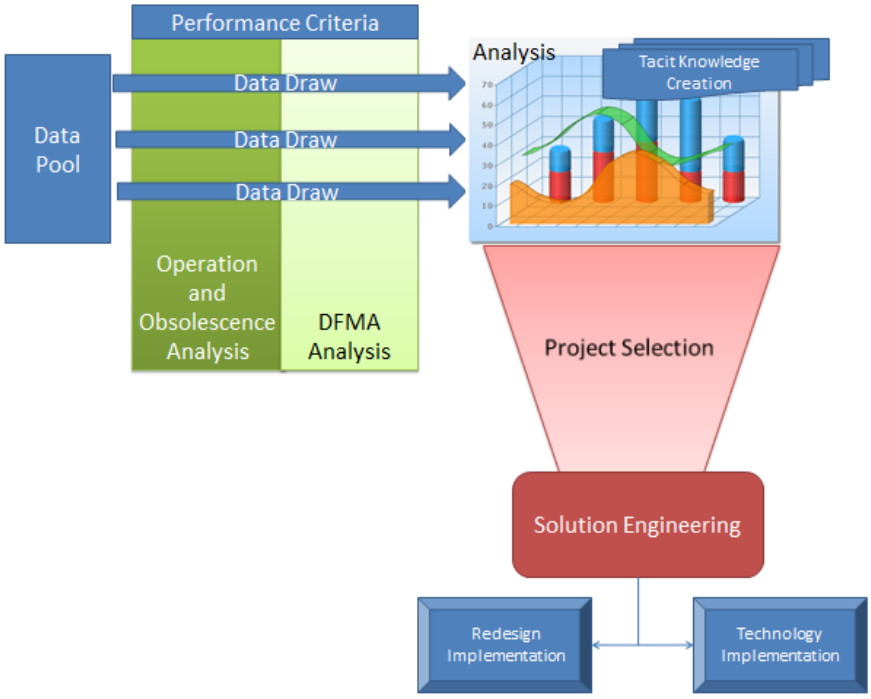


Figure 4-1 Redesign for Assembly Method

The first phase of this Methodology is the identification and collection of data and the creation of a data pool. The second part is the identification of critical performance criteria that are made up of two categories. The first category is

measurable criteria related to traditional DFMA. The second category, are factors that are unique to products that are already in production.

Once a pool of data is created, the next step is data mining. In any given investigation, certain criteria will take precedence depending on the objective of the study. For example, if reducing assembly time is a current objective then indicators that provide information on time and efficiency will take precedence. At this stage, the most relevant performance criteria are selected to act as a data filter. Once this takes place, effective data can be drawn from the previously assembled data pool. This methodology is unique in that it considers manufacturing enablement through design after a product is in steady state production. The methodology takes into account both traditional Design for Assembly techniques as well as specific factors related to Redesign for Assembly. As mentioned previously, traditional DFMA techniques tend towards initial development of products through concurrent consideration of design, manufacture and assembly. Redesign for Assembly aims to do this whilst also acknowledging the restrictions that a steady state product has to navigate through and also the advantages in available data that a live product provides.

Analysis of this filtered data leads to the creation of recorded tacit knowledge. This is defined by Groff and Jones, (2003) as personal knowledge embedded in individual experience. It involves intangible factors such as opinions, perspective and values. This type of knowledge is more difficult to record and transfer.

The creation of knowledge in turn leads to the project selection stage. Depending on a company's current strategy, projects will be selected according to the most valuable criteria at that time. After project selection, the projects are taken into development stage, named the Solution Engineering phase. As discussed, solution engineering is not the goal of this method but it needs to be

acknowledged. It is intended that the analysis phases, specifically the obsolescence analysis will provide a strong indication of a potential project direction.

4.2.1 Tool Creation

From the previously discussed methodology, the most critical aspect is the section where data is drawn through the performance criteria. Therefore the development of a tool to implement the stated methodology in that area is proposed. The tool will provide quantitative results to compare processes against each other. Therefore, the first task in putting together such a tool is to identify measurable factors that can provide data.

Four groups of stakeholders were approached separately in pursuit of establishing this criteria. They were also asked to offer their opinions on potential DFA projects in the hope that some consistent parallels could be drawn from each group. The four groups were as follows:

- Operations and Manufacturing Engineers; These are directly involved in manufacturing improvement projects and day to day running of production
- Industrial Architects; this is a body that attempts to link manufacturing improvement with engineering improvement.
- Engineering Continuous Improvement; These are engineers that typically work on performance improvement for the aircraft.
- Research and Technology; This is a team that develops assembly and manufacturing technology and processes.

These are all separate roles and members of each function do not assume responsibilities of other functions.

Group	Feedback
Operations and Manufacturing Engineers	Cost and Failure are the main drivers to target. Suggested projects were small scale projects that would not payback after a design change. An example was certain features being too close to a work area prohibiting the use of a faster tool.
Industrial Architect	Cost, failure and also performance improvement were projects that the Industrial architect is interested in.
Engineering Continuous Improvement	Aircraft performance improvement were key for any project in this team, some isolation from manufacturing was prevalent with manufacturing projects only considered as part of larger engineering improvement projects.
Research and Technology	Technology Obsolescence and recurring cost improvement were the main drivers behind projects in the Research team.

Table 4-2 Discussing the stakeholders engaged to define performance criteria

Four main broad criteria groups emerge from Table 4-2. These are as follows:

- Failure Analysis
- Cost
- Operation Difficulty
- Market Changes and Obsolescence

Failure Analysis:

Failure is anything during the manufacture phase that contributes to further unplanned costs. Through this investigation it was observed that failures that affect the performance of the product are most critical and thus they are taken most seriously. As such these failures go through analysis to eliminate recurrence or solutions are engineered in advance to address them before they occur. However, as per the definition stated previously, these are not the only failures that are interesting to this investigation. This tool will attempt to capture those failures through engaging with the specific operators and manufacturing engineers that work in that process. The most direct way of capturing this data is through disruption time. However, this is not easily accessible as disruption time is classified into several categories and those categories are presented as time figures that capture other areas of disruption. Therefore, failure will be captured in the operation difficulty assessment as a question that is answered through feedback from the operators. This is captured in Table 4-5.

Cost:

In any manufacturing business, operations are mapped out in great detail with time allocations identified. There are three main inputs that can provide useful data for this analysis. They are as follows:

- Work content tracker: Captures operation order and flow as well as the number of operators assigned to work on particular tasks.

- Standard Time intervals, man hours and number of operators: Captures all time related aspects of an operation
- Critical Path: Captures the operations that lie on the critical path of production

Cost carries the heaviest weighted factor that will feed into this model. Depending on the scenario that the program is operating in different weight allocations will be given to hours that can potentially be saved. If for example, the company has an overall drive to reduce the total number of man hours during wing assembly then any hour that can be saved becomes critical. If however, the company is looking to increase production rates, then special emphasise will be placed on hours that lie on the critical path. Three measurable factors will be used to compare the impact of cost on different processes. They are:

- Overall number of hours allocated to the completion of a process.
- Critical path time
- Number of Operators involved in a single assembly process.

Operation Difficulty:

The following methodologies have been developed in the past with a view to operation difficulty:

- Handling score (Hitachi Assemblability Method)
- Number of Parts and nature of activity (Boothroyd and Dewhurst)
- Assembly Plan Evaluation (Hsu)
- Accessibility (Hsu and Lin)

A method to determine a quantitative number that can provide an indicator to operation difficulty using an adaptation of these methodologies is required. The proposed method is developed specifically for wing box assembly in a large

commercial aircraft manufacturer. In order for it to be used in any alternative capacity the questions that are asked will need to be tailored for that assembly environment. The main assembly activities are categorised and analysed in terms of complexity. The main operations that wing box assembly consists of can be categorised as follows:

- Clamping
- Drilling
- Sealing
- Bolting
- Cleaning
- Measuring/Checking

The way the analysis has been set up is that each operation is raised and the complexity of the operation is assessed based on a series of questions. Each set of questions provide a number that are summed together. A higher number indicates a higher operational complexity or difficulty. As well as these operation specific questions a number of overall operation questions. These questions take into account the total number of components involved in the activity and the total number of operations. This tool also assesses the level of value being added by the operation. For example, a measurement operation or a cleaning operation is essential but could be better served with an embedded solution or a more efficient process in the case of cleaning. The more variety involved in a process, the higher the operation difficulty number will be. The measurables that are collected from this aspect are as follows:

- Operation Difficulty Score

- Number of components
- Number of process actions

Market Changes and Obsolescence:

This appears to be the main contributing factor for a steady state production system. The amount of saving or cost opportunities that are not exploited due to obsolescence is immeasurable.

Obsolescence in this context is process obsolescence. As mentioned previously, suppliers are unlikely to stop providing a product or service required by a large OEM, this is especially true in a long life product such as an aircraft. This does not mean that they will cease to develop better products. The moment a competitor takes advantage of a manufacturing technology that is superior to the one currently employed, that technology begins to become obsolete. The extent of that obsolescence depends on the level of advantage provided. This at first seems like technology insertion with no place in a DFA analysis. However, these researchers have encountered multiple instances where an available technology that can provide significant improvement to assembly is discarded because the current product design is not able to accommodate that technology. This is one aspect of obsolescence.

The second aspect of obsolescence is a knowledge management recirculation issue. It would be prudent for manufacturers to superimpose their new processes on their older products. The literature review discussed knowledge management techniques in addressing this issue. The most relevant work, carried out by Zheng and Terpenny, 2013, attempted to address the issue through the implementation of a hybrid ontology approach. The most pertinent aspect of this approach is a method to effectively communicate the realities of obsolescence when addressing

particular technologies. It is difficult to do this quantitatively as indicators such as cost and time saved cannot be compared for technologies with different scopes. The researcher proposes a gated classification process to categorise the level of obsolescence of the process under analysis. The following defined Obsolescence Impact (OBI) Factors are proposed:

OBI 1
Process or technology is State of the Art and is being utilised efficiently.
There are no updated techniques for this process and no visible opportunities for improvement.
OBI 2
The technology or process is still current and serves its purpose well however there are potential improvements being developed.
There are immature technologies being developed but their capability is unknown.
OBI 3
Immature technologies or processes have been developed outside of the business but it is unknown how effective they will be.
The process or technology is still functional and is not considered a risk in the immediate future.
OBI 4
Technology is out dated and whilst it functions correctly there are mature off the shelf solutions that can improve the process

Processes have been superseded outside of the business but have not been demonstrated specifically in the targeted business area.
Processes have not been superseded inside of the business.
If this process is not addressed it will become a bottleneck in the future.
OBI 5
The process or technology is out of date
The process is a bottle neck in the manufacturing assembly line
Mature Processes have been developed and implemented to address this area in other parts of the business
Mature Technologies are currently being used by competitors for this process or a process very similar to it.

Table 4-3 Obsolescence Impact Score Criteria

It should be noted that the improvement, mentioned in Table 4-3, is defined as whether the process or technology has been superseded elsewhere to mature level.

It is important to note that the quality of the benchmarking exercise is critical in determining an accurate OBI score.

This method also answers the question posed in Chapter 2 of "how can the manufacturer realise when to take advantage of improved analysis techniques that can potentially lead to relaxed assembly and manufacturing requirements?" The benchmarking exercises is carried out on processes across multiple products. Newer products that have benefited from the latest analysis techniques

will highlight their benefits potentially creating a path for those techniques and benefits to be implemented on legacy products.

4.2.2 Redesign for Assembly Tool

With these criteria in mind the tool is demonstrated below. The proposed tool was applied to the scenario of the installation of brackets that are bolted onto the structural stiffeners of an aircraft wing skin and to the wing ribs. Due to the confined nature of where they are installed the use of the latest drilling machines is unavailable. The values shown are not real values for confidentiality reasons. However the conclusions drawn are based on the real values and are still valid.

4.2.3 Case Study

Setting the Problem:

To test the methodology being proposed in this work a case study with a known outcome is used. The case study looks at the installation of a large number of butterfly brackets, known as cleats. The problem has been persistent despite several attempts to find solutions through technology. Recently, a proposal to design out these butterfly brackets has been accepted and when completed will offer considerable assembly savings. As this case has a known Redesign for Assembly outcome, it provides an ideal case study to measure the effectiveness of the tool. The location of these cleats is shown in Figure 4-2 and the an example of a cleat is shown in Figure 4-3.

The wing box is assembled in a section during production labelled Stage01. This is consistent for the Single Aisle, Long Range and A380 aircraft. In general, the majority of required holes are now drilled using a semi-automated drilling process using a drilling unit called an ADU (automated drilling unit). This process involves the use of thick templates that act as fixtures for the drilling unit to drill a hole with

a countersink in one single operation. Previously, to drill a hole to the required tolerances a multi-step progressive drilling method was used that involved the following steps

- Pilot Hole
- First Size
- Down Size
- Reaming
- Countersink Cage

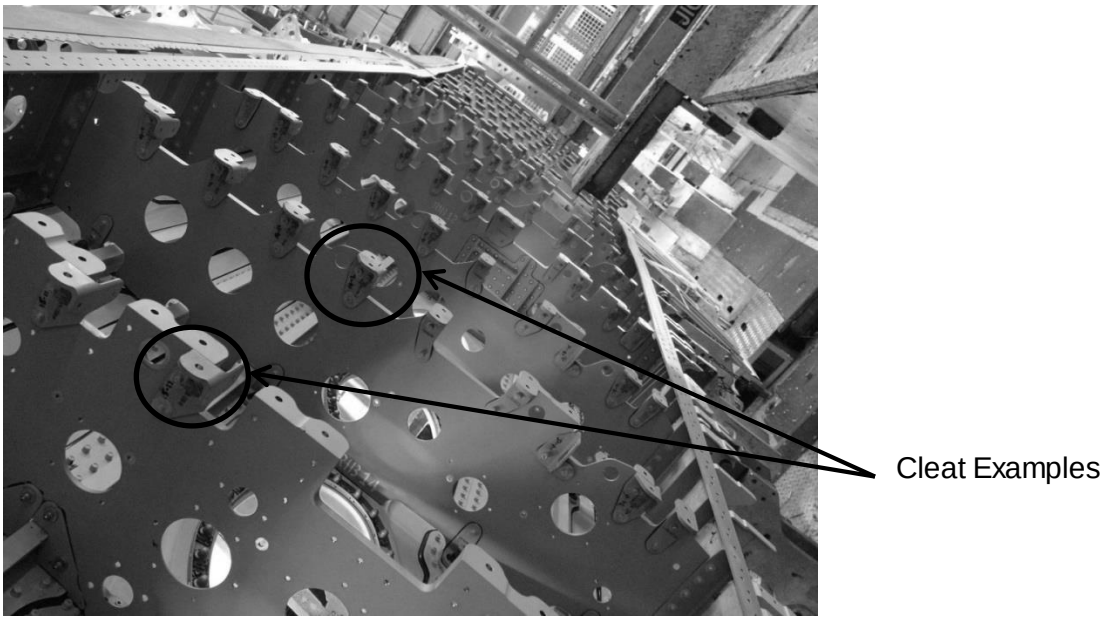


Figure 4-2 Showing Butterfly brackets bolted onto wing ribs

With the introduction of Automated Drilling units ADU, cycle time has been reduced dramatically by removing several drilling passes. These ADU are used to carry out the majority of drilling operations on areas that have large collections of holes.

There are some areas that did not benefit from the deployment of ADU's. One such area is cleat installation. Cleats are butterfly brackets that are bolted onto the structural stringers on the wing skin and to the wing ribs. These brackets offer

extra support, strengthening the interface between the Wing Skin and the Ribs. Due to the confined nature of where they are installed, the use of current ADU is unavailable. Therefore, the process of drilling these butterfly brackets has remained as before.



Figure 4-3 Showing a Cleat bracket

Cleat Drilling Process:

The cleat installation process is listed as follows:

1. Collect equipment
2. Ensure work area is clean and clear
3. Check and mark edge distances as per drawing
4. Clamp cleat to stringer
5. Pilot forward rib hole and pin
6. Pilot stringer hole and pin
7. Pilot remaining holes and pin stringer hole
8. Open aft rib hole to requirement and check
9. Open stringer hole to requirement and check
10. Repeat for remaining holes
11. Remove cleat (unpin rib last)
12. De-burr
13. Remove swarf

The process is complex and the working conditions are confined. Pilot holes are drilled on the cleats during their manufacture. These holes are then transferred to the adjacent structure after locating and clamping individual cleats in position. As well as the many steps involved in drilling each hole of each cleat, there are a variety of cleats differing by shape, dimensions and hole locations. Therefore, as well as the many drilling steps for each hole in each cleat, the hole positions vary on the cleats themselves. This adds an extra step on each drilling operation for measurement. In one particular aircraft there are 123 cleat variations. In total there are 150 cleats are installed. Many of these cleats are similar in shape but have slight differences in dimensions. Many times dimensions vary from one cleat to the next by 0.1 mm or 0.2 mm. The most commonly occurring cleat shape is the butterfly shape shown below in Figure 4-4. In this shape alone there are 42 different variations.

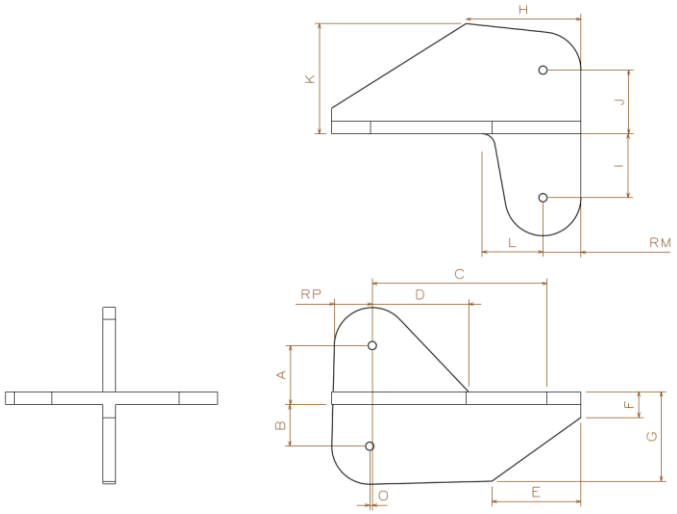


Figure 4-4 Showing a typical Butterfly Cleat

The number of variations in cleats is an example of the pre-DFMA culture during product development. Design engineers were following strict design rules driven by weight reduction targets. From the design engineers' point of view,

standardising the cleat shape would serve no purpose as at that time, every cleat would still need to be measured and installed. For the manufacturing engineer, the variation in cleat shapes and dimensions creates two problems. The first is that simplifying this task becomes very difficult if a solution is sought through technology insertion. Typically, implementing an automated or tooling solution requires a stable process with minimal variation lest the costs escalate and become unfeasible. The second is that this manual, variable task; creates an environment where errors are more likely to occur.

Due to the reasons mentioned, technology solutions would be very costly in this area and thus an alternative solution would be beneficial. The proposed tool is thus used to demonstrate that a DFA solution is a more interesting prospect.

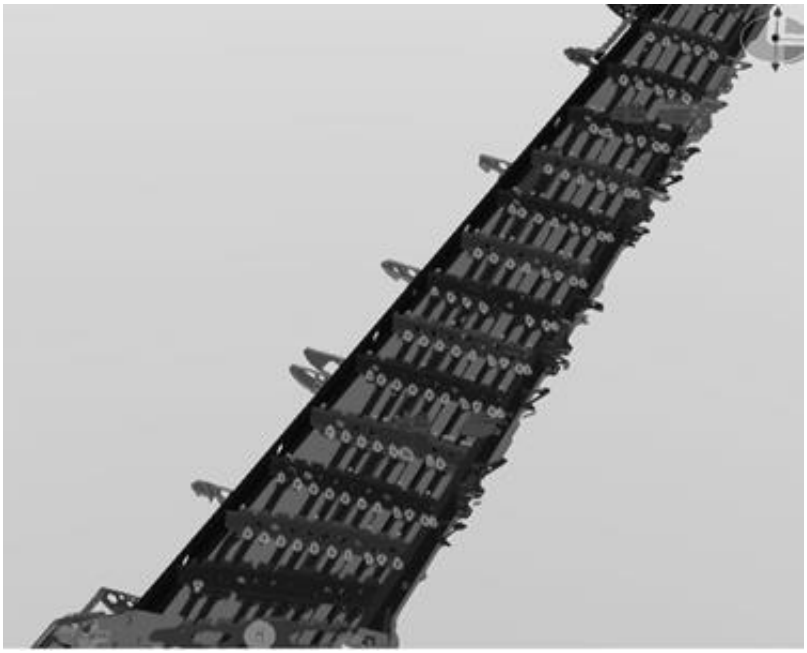


Figure 4-5 Visual Demonstration of where Cleats appear in a wing box

4.3 TOOL DEMONSTRATION

4.3.1 Cycle time and Cost

Drilling of Brackets	Per Wing Set	Per Single Wing
Overall Operation Man hours	60	30
Critical Path (hours)	10	5
Number of operators	12	6

Table 4-4 Real values not shown.

The cycle time and cost for this area is summarised as follows, 5 operators are required for a shift of 8 hours to complete the full set.

4.3.2 Failures

As mentioned previously, recorded data for failures is not captured in a method that can be used in this kind of analysis. The proposed method is to capture feedback from the operations teams for the individual work packages. The input into the proposed tool will be a positive or negative response. Failures and rework will appear as a single numeric in this tool; either they will be listed as an issue or they will not.

4.3.3 Operation Difficulty Score

The operation difficulty score is calculated using a set of questions displayed in Table 4-5. It should be noted that the series of questions are unique to this

manufacturing system. A unique set of questions to achieve a operation difficulty score is required to be developed for every unique manufacturing system. For example, the questions shown in Table 4-5 are only applicable to the wing box assembly area. They are not applicable to the next stage of wing production; system installation.

There are two notable numerical values that are gained in the analysis shown. They are the operation difficult score and the number of operations. The operation difficulty score sums together the number of different types of operations, for example, if the operation involves a drilling, bolting and sealing activity, these will sum together as 3. The operation difficulty score also takes into account the difficulty of those activities. For every further complication an extra 1 is added to the operation difficulty score. For example, if a drilling operation is a single pass this will merely count as one. However, if the drilling activity requires several passes, along with changes in tooling or cutter size then this is a further complication and thus will be counted as 2.

The second significant numeric that appears in Table 4-5, is the number of actions that take place in the operation. This is a count of the number of actions that the operator is required to carry out to complete the package of work. For example, one drill cycle would count as one action. If, to complete a hole, several drill cycles are required, this would count as several actions. Together with the operation difficulty score, these two factors provide a top level and superficial view of the operation difficulty that can be used to make quick assessments.

Clamping Operation	Is there a clamping operation	Is access required from both sides of work piece	Can the force being applied damage the work piece	Is more than one operator required to apply the clamp	Access: Is the working area visible to the operator during the operation	Access: Is the operator required to strain to reach the working area
	yes	yes	no	no	yes	yes

Drilling Operation	Is there a drilling operation	Are drilling jigs required	Is more then one operator required to install the jigs	How many passes must be drilled before the final hole is produced	How often is a temporary fastener inserted	Access: Is line of sight not available
	yes	yes	no	3	3	no

Sealant Operation	Is there a Sealant operation	Does cleaning need to take place	Access: Is the working area visible to the operator during the operation	Access: Is the operator required to strain to reach the working area
	no	N/A	N/A	N/A

Bolting Operation	Is there a bolting operation	Is access required from both sides of the work piece	Can a single operator access both sides	Access: Is the working area visible to the operator during the operation	Access: Is the operator required to strain to reach the working area
	no	N/A	N/A	N/A	N/A

How Many parts are to be assembled	150
How many operations take place in total	3075

	Can the part be lifted manually?	How many people are required to lift and position	Is a measurement using metrology equipment required?	Is a check required using a tool such go-no go gauge?
Lifting	yes	1	no	yes

Non value adding operations (such as cleaning) or parts not fitting	75	Fettling operations

Operation Difficulty Score	13

Table 4-5 Operation Difficulty Score

4.3.4 Obsolescence

Internal factors
Long Range Aircraft have standardised cleats. New stress and structural analysis methods open the possibility for Cleat deletion.

New Technology Developments	**Maturity**	**Comments**
Confined space robot: Snake Arm Robot	Low	Prohibitive Price and lack of effective payload capability
Advances in drilling capability	Low	

Obsolescence Impact Rating

1-5
1-Little to no Impact
5-Process or technology are highly outdated

Assessment	**4**

Table 4-6 Obsolescence Impact score

As discussed previously, the Obsolescence analysis is difficult to quantify. The author has proposed an obsolescence impact score that requires the user to make a judgement based on gathered data. The two streams of data that are required to be collected are “changes to the process or part that are present in more recent products” and a technological assessment of what is available throughout the industry. The first set of data is easier to acquire and is definitive. The second set of data requires an engineer with experience in the particular field of technology to carry out a minor benchmarking analysis. The risk here is overlooking technology or not having exposure to a particular technology. The impact score is assigned from 1-5. An impact score of 1 means that the current process is not obsolete and an impact score of 5 indicates that there is room for possible improvement.

In this case, the score provided is 4 due to the acknowledgement that it falls under the OBI characterisation from Table 4-3 of “if this process is not addressed it will become a bottleneck in the future”. A benchmarking exercise on potential technology was carried out and despite the passage of several decades since this process was introduced, a cost effective technology is still not available.

The main reason the obsolescence impact score in Table 4-6 is high is because of the development of new stress and structural analysis methods. These have enabled studies to take place that have allowed an aircraft in a different program to benefit from cleat standardisation. Also, these methods have enabled an analysis that has indicated that cleat deletion is now also a possibility.

4.4 DISCUSSION

Operation Difficulty Score	**	
Failure Score	*	
Number of Actions	*	
Number of components Assembled	*	
Overall Operation Man hours	*	Hours
Critical Path	*	Hours
Number of Men	*	
Ratio of Men to Operations	*	Hours/operator
Non-Value Adding Operations	*	Percent
Obsolescence Impact Score	*	

Table 4-7 Showing the various Design for Assembly Factors proposed in the methodology. (No values shown)

Table 4-7 shows the results that would be generated by the proposed tool and methodology. The problem with any acquired data is that there is nothing to compare it against and therefore they are currently meaningless. In order for the tool and methodology to be effective, more data is required to create comparison scenarios.

One problem is the identification of which operations to analyse. The detailed analysis carried out for the cleat drilling operations will take a very long time to be carried out on every operation in wing box assembly. A shorter approach is therefore required to identify which operations should be analysed to this level of data. As discussed previously, the biggest driver in manufacturing and assembly improvement has always been the number of hours saved. A more recent driver that provides further direction is a reduction in the critical path. As such, the Author has proposed the use of a two tiered approach. The first filter will organise operations based on the number of hours that lie on the critical path of wing box

assembly. The second filter will organise the operations based on the total number of hours involved.

4.5 CONCLUSIONS

A new empirical method has been developed to offer DFA support on legacy products. The method is successful. The reliance on existing data inevitably means that the results are relevant. The innovation of the tool is manipulating that existing data into meaningful DFA messages and enables an engineer to make an informed decision

To ensure that the tool can indeed do this Section 7.2 carries out a more extensive validation exercise.

5. COMPLEXITY ANALYSIS

5.1 INTRODUCTION

Chapter 4 developed a method for retrospective application of design for assembly principles on existing products that took into account the reality of those products. The aim of that chapter was to deal with existing products. The aim of this chapter is to develop a method that can provide DFA analysis for existing products as well as future products in the aerospace context.

This chapter will initially go through some of the shortcomings of the method described in Chapter 4. Then the chapter will go on to discuss the advantages of a complexity analysis carried out on a macro scale. After this, a discussion is presented on the positive and negative aspects of how macro analysis takes place today. A methodology for complexity analysis is then presented that is also refined for the context of this research. This methodology is then applied using real data and the results are presented and discussed. Finally conclusions are drawn about the results and the chapter ends with a discussion on the merits and failings of the methodology.

5.1.1 Deficiencies in Redesign method

As mentioned in the summary of the previous chapter, the redesign method that was outlined provided a strong comparison tool for processes that were in existing production systems. The analysis was designed to be carried out as an exercise that relied mostly on available data thus reducing the time that is normally taken in gathering data. The tool and analysis were deficient in one particular aspect. This aspect was that the method required input from knowledgeable stakeholders to decide which processes were to be chosen. Thus

the whole manufacturing system, encompassing every process, was not compared together. The reason behind this was because of the level of detail required for each analysis. Putting together such an analysis with the previously proposed method would be highly time consuming and therefore a macro view of a production system using this method is unlikely to happen. Such a view would be advantageous to both legacy production systems for either redesign or technology insertion purposes as well as product development. A macro view would provide the following advantages for the engineer:

1. Highlight bottleneck areas.
2. Traceability of where problem areas start and how they progress in a manufacturing system.
3. Easier identification of trends that can be linked to elements of the manufacturing system.

Traditionally such a macro view is carried out using time allocation of activities and processes. Using cycle time analysis, bottle neck processes can be identified and line balancing activities can take place. However, a pure time analysis misses potentially advantageous elements. Previously discussed literature points to the merits of assessing operation difficulty and obsolescence in seeking improvement opportunities. Further, the previous chapter discussed the advantages of DFA analysis even on legacy products. In a time based analysis those are only assessed if there are cycle time issues in those particular areas. Widening the analysis to encompass the majority of the processes in a macro analysis provides several advantages such as:

- Identification of areas of frequent failures and failure trends.
- Identification of areas where trends start.

One of the reasons that a cycle time analysis is often carried out is due to the simplicity of a single metric that is unanimously agreed to be critical. This chapter will aim to develop a metric that combines several critical factors that can also be used in a macro analysis. Also, this research will aim to draw meaning from trends that appear across a macro analysis that engineers can understand immediately. The metric will aim to measure complexity.

As discussed in the literature previously, there is no universal definition of complexity. In each case it is defined according to its scenario. In this case, the definition of complexity being proposed is as follows:

"The challenges faced by the manufacturing and assembly system from component design, technology and physical aspects within the specific context of a particular industry."

The three aspects mentioned in this definition are chosen due to them being the three aspects that complete the manufacturing system.

5.1.2 Highlighting how complexity analysis is advantageous to large volume assembly.

In Chapter 4, the specific nature of wing box assembly in a DFMA context is discussed. These aspects are mentioned again below:

- *Large Volume Components:* A wing has a span of around 15m. The wing assembly is held in large monument tooling structures.
- *Accuracy of Assembly:* Aerospace assembly operates with positional accuracy of 0.2mm. When coupled with the size of the components, achieving that accuracy becomes difficult due to challenges in manipulating components and elastic movement of the components.

- *Long life products:* Aircraft can be in production for decades. This leads to initial assembly and manufacturing technology being superseded potentially giving competitors an advantage.
- *Risk Averse Business Model:* Such is the competition in the commercial aircraft sector, that the traditional approach has been a reluctance to adopt any change in assembly and manufacturing that could compromise delivery. In recent years, there has been a shift towards a renewed focus on profitability as well as sales.

The result of the previous chapters analysis was the development of metrics for obsolescence impact and operation difficulty. A complexity metric will include some of these aspects but unlike that deeper process analysis, this metric aims to take a step back and combine a number of indicative factors that can provide a more general indication.

5.1.3 General Observations – current state in Airbus

The sponsor company, Airbus, carry out assembly optimisation exercises on every product regularly. As mentioned before, analysis is predominantly focused on time. As the area of focus for this research is the wing box assembly, observation of how optimisation activities take place has been carried out here. As is common for manufacturing businesses, there is a central area where performance criteria are displayed. The main performance criteria displayed are cycle time and failures. If consistent problems reveal themselves according to these two issues, then projects are launched in separate functions. Typical projects that are launched are technology insertion projects and lean improvement projects. Issues with consistent failures may sometimes lead to

design modifications. Typically, the cost of design changes far outweighs the advantage to be gained from minor failure correction.

This approach is not just common in the aerospace industry, but rather it is widespread across most manufacturing systems. A number of issues present themselves with this kind of approach:

1. There is no holistic approach to analysing a manufacturing system that includes time data, DFA and operational factors. An analysis of the components and manufacturing system together will provide an insight that cannot be gleaned through viewing these aspects separately.
2. There is no indication of quality impact in a pure time based analysis. Failures or time deviation is usually recorded but only major consistent failures will lead to design modifications. When planning future production processes, a pure time based estimation analysis cannot give a strong indication as to where potential failure may take place.

5.1.4 Cycle Time Analysis Demonstration

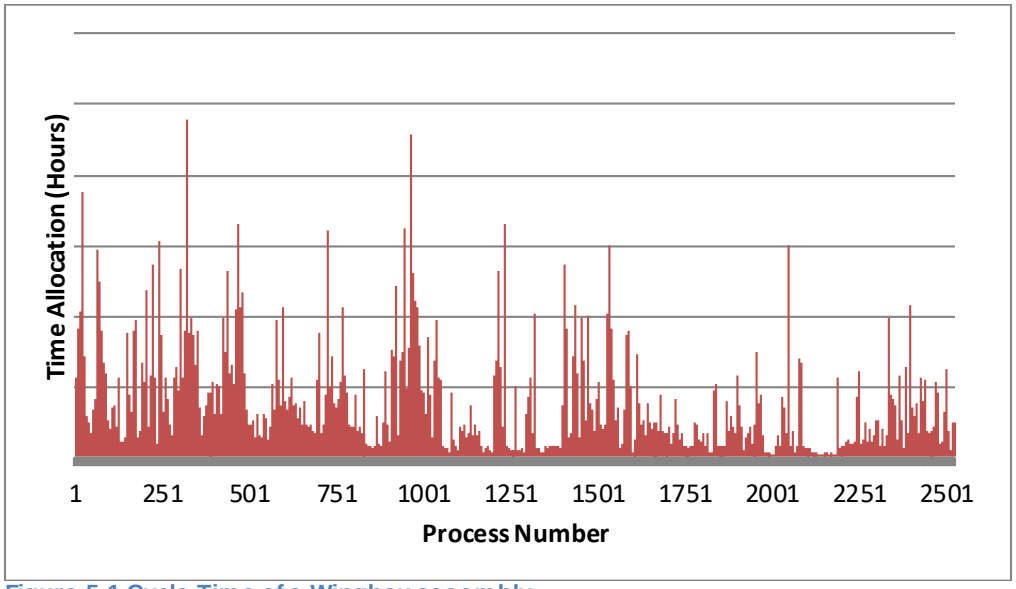


Figure 5-1 Cycle Time of a Wingbox assembly

Figure 5-1 shows the time allocations for all the processes during wing box assembly as provided by the sponsor company. The data is mined from industrial engineering studies. As mentioned before, each process is allocated a reference number and a document is produced detailing the activities within that process. Inside that document small packets of work, usually the same activity, are labelled as phases. Figure 5-1 depicts the time allocations of those phases on an x-axis that represents the order they take place in.

Two patterns stand out for analysis within Figure 5-1. The first is operations of consecutive processes with consistent time allocations.

This is demonstrated below in Figure 5-2 and Figure 5-3.

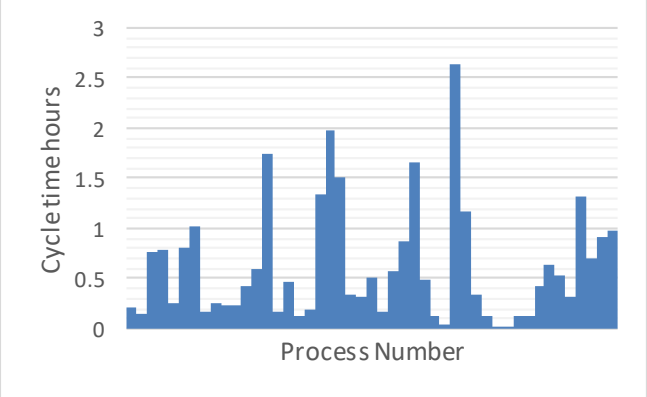


Figure 5-2 showing a grouping of consecutive operations that have high time allocations.

Figure 5-2 shows operations that take place within the same packet of work where each subsequent step has a high time allocation.

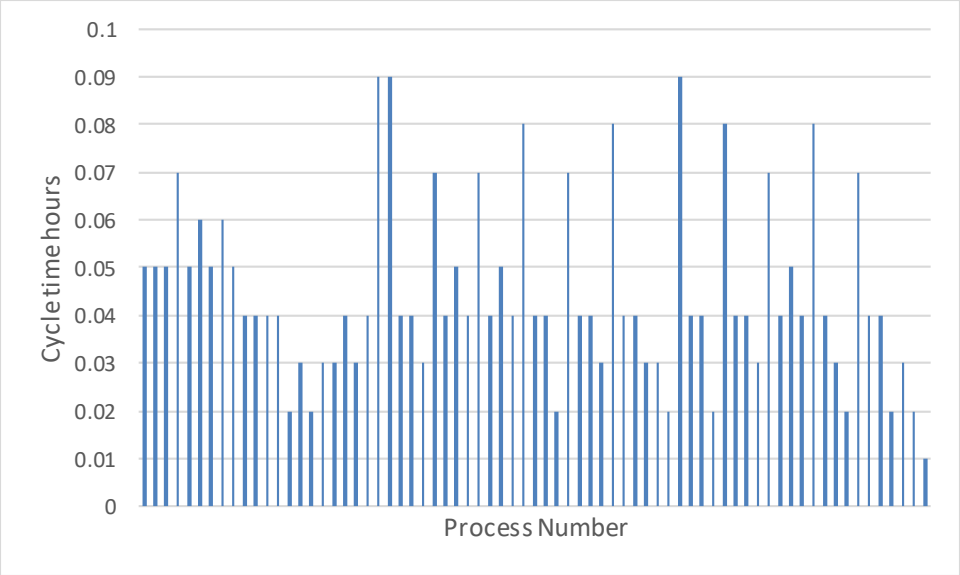


Figure 5-3 showing processes that appear together with low time allocation

In both cases, these are activities that are carried out typically by the same operator working on a particular process. In the case of areas with consistent low time allocations, this could be indicative of an area that could benefit from the introduction of automation technology. Alternatively areas of consistent high time allocations could be indicative of areas that are ripe for a design change.
The other striking feature of Figure 5-1, are areas with no consistency. This could be indicative of a process that is highly complex in some activities and simple in others.

The problem with a pure time analysis is that without further investigation these suggestions are useless. Patterns identified in a pure time analysis need more context to provide reasonable suggestions or conclusions. Thus, it is proposed that a complexity analysis is combined with a cycle time analysis to provide that context.

5.2 COMPLEXITY METHODOLOGY

As has been discussed in the literature (Park and Kremer, 2015) complexity as a definition depends on the scenario being discussed. Thus, a complexity analysis is dependent on its scenario. As such the following method is proposed in creating a complexity analysis technique. The method is directed towards macro analysis of a manufacturing system.

1. Define Complexity for the specific scenario
2. Identify contributing factors
3. Measure those factors
4. Create Macro Analysis
5. Introduce Controls
6. Draw Conclusions

Define Complexity for a specific scenario:

The literature review highlights that complexity has been adapted depending on the application or scenario. This methodology requires complexity to pass through several filters before it can be used effectively. The first such filter is that this definition of complexity is applicable to a manufacturing assembly environment and is not useful for other applications.

Identify Contributing Factors:

The definition of complexity should enable the engineer to recognise what is a complex environment. This stage should involve stakeholders familiar with the manufacturing assembly system. The stage requires historical data and knowledge in order for future product development to be effective. The suggested

strategy is to analyse extreme cases of complexity and lack of complexity and identify the differences. For example, if a current product has two drilling processes, one with a high number of failures that has a longer associated assembly time and the other which has fewer complications with perhaps more holes being drilled in less time, then a quick comparison of the differences of those processes can indicate contributing factors towards complexity. It is important to note that the factors identified should be measureable and transferable to other processes within the manufacturing system.

Measure Those Factors

In this stage of the methodology data is collected using the previously identified contributing factors. It is recommended that an initial historical analysis on a similar product should be carried out first in order to test the strength of the analysis before applying it to a future product development scenario.

Create Macro Analysis and Introduce Controls

The macro analysis enables the engineer to compare complexity data throughout the whole manufacturing system. It is important that controls are included in this analysis. These are processes that are well known to have certain levels of complexity. This enables the engineer to assess the usefulness of the analysis.

Draw Conclusions

A historical exercise of a previously implemented product is required for trends to be identified. In a historical analysis, there are known outcomes. Complexity trends can be matched to these outcomes. For example a set of process that have a low average complexity or display a particular trend may correspond to an area that can be automated. If this is established in multiple instances in historical

data then a trend conclusion can be drawn and used to understand complexity data from a future product development situation.

5.2.1 Defining complexity for aerospace assembly

By combining factors that influence complexity from previous work, DFMA and the context of this particular scenario several complexity factors are identified.

The complexity analysis aims to analyse the assembly processes and the design processes simultaneously to draw conclusions for assembly optimisation through DFMA.

In this context, the factors that are of interest are component or assembly features that directly impact manufacturing performance on an individual process level. The following factors are drawn from the previous literature and from expert recommendations from the sponsor company.

- Number of Components
- Number of Interfaces
- Working area volume
- Visibility
- Material
- Information flow; process variation/consistency

Number of components: As demonstrated by Boothroyd and Dewhurst (1994), reducing the number of components will reduce assembly time and reduce the risk of assembly failures.

Number of Interfaces: These are the number of components that the work in progress interfaces with. For example, when assembling a rib, the rib interfaces with the rear and front spars and thus interacts with 2 interfaces. The number of interfaces has a bearing on positioning the part and likely increases the tooling requirements and the required setup time

Working Area volume: This is particularly relevant for large volume assemblies where components are likely required to be installed in small working areas such as rib bays. A cramped area introduces ergonomic issues and likely leads to increased risk of assembly failures (Falck, Örtengren and Högberg, 2009).

Visibility: This is the access that the operators have to view the work piece from useful vantage points.

Material: Also discussed by Boothroyd and Dewhurst (1994). Consistent materials allow for manufacturing process consistency in harmonising tools. Necessary material variation introduces complexity in the form of differing tools, processes and increased variability and thus quality risk.

	Factors to Consider	Measure
Number of Components	The number of components being directly affected at the working area. For example, when assembling a rib to two spars, then the number of components is three	Number of components
Number of Interfaces	This is the number of interfaces between the components. In the rib example above, there are two interfaces, the rib to the front spar and the rib to the rear spar.	Number of Interfaces
Working area volume	This is the space available to an operator to carry out assembly activities. The operator could be operating in an enclosed space or an open space and this will affect their ability to carry out the assembly.	Volume Measure
Visibility	This is a measure of whether the operator is able to view the assembly area being affected. For the purposes of this method there are two options, either Full visibility of the work piece from every advantageous angle is available or it isn't.	Binary

Material	In Wing Box assembly there are two main materials that form part of the structure and that machining operations take place on. These are aerospace grade Aluminium and Titanium. Aluminium forms the majority of the product and is considered the default material in this analysis. Special dispensation is made for areas that require titanium machining.	Binary
Process Variation	This is a measure of the repeatability of the process. It is carried out by taking an average of the time differences between consecutive processes.	Average Time Interval Variation

Table 5-1 Proposed Complexity Factors

A common feature of the factors shown in Table 5-1 is that they can be measured simply. When these factors are combined together in a single metric they provide a common factor that all processes can be measured against. This is demonstrated in the following section.

Notably, the size of the component and its handling is not used as an indicator for complexity. Throughout this investigation, only one major process is affected significantly by the size of the components from a handling perspective. This is rib installation. In other instances there are short, operator intensive dedicated activities for location of major components. This includes positioning of the spars and wing covers. Therefore, including component size and handling as complexity factors was deemed unnecessary. This is further elaborated on in section 5.3.

5.2.2 Application

The next part of developing this metric is deciding where to apply this measurement and how to combine the factors together. A demonstration of the proposed factors is shown below on a process installing a rib onto the spars. The values discussed below and shown in **Error! Reference source not found.** are not real but are used to demonstrate how the method is applied.

Number of Components: 3

This is the rib itself and the two spars that it is being attached to.

Number of Interfaces: 2

The interface between the rib and the front spar is counted as one, as is the interface between the rib and the rear spar.

Working area volume: 3 m^3

The operator in this instance is working on an open area with no restriction to his movement. 3 m^3 serves as an expression that the operator can access his surroundings with ease.

Visibility: Full Visibility listed as 1

There is no obstruction of visibility and thus it is classified as 1. Any obstruction to visibility or access would classify the process as 2.

Material:1

There are two options under this factor. The choice is between Aluminium (1) or Titanium (2). Any operation that involves a combination of these two materials would be listed as 2 as any inclusion of Titanium adds complexity.

Process Variation: This is measured by taking an average of the differences in time allocations of consecutive processes. This is demonstrated in the below table:

Table 5-2 Demonstrating how Average Time Variation is Calculated

Activity	Allocated Time in decimal hours	Time Difference between consecutive Activities	Average Time difference
Load Part 1	0.12	-	-
Load Part 2	0.14	0.02	0.057
Load Part 3	0.11	0.03	0.057
Load Part 4	0.23	0.12	0.057

Table 5-3 Demonstration of Complexity Factors being combined

Complexity Factors	Allocation or Value	Complexity Translation
Number of Components	3	75
Number of Interfaces	2	66
Working area volume	3	1
Visibility	1	50
Material	1	50
Process Variation	0.057	5.7
	Combined Complexity Metric	247.7

The third column of **Error! Reference source not found.** is titled complexity translation. In this column the values from the previous column are multiplied by a transformation factor to make them relative factors. The translation factors are shown below. The aim of these translation factors is to bring the values within the same orders of magnitude.

Table 5-4 Showing complexity factors translation calculation

Complexity Factors	Allocation or Value	Translation formula	Complexity Translation
Number of Components	3	Multiply by 25	75
Number of Interfaces	2	Multiply by 33	66
Working area volume	3	100- (allocation value *33)	1
Visibility	1	value multiplied by 50	50
Material	1	value multiplied by 50	50
Process Variation	0.057	Value multiplied by 100	5.7
	Combined Complexity Metric		247.7

They are then summed together. In this case the total complexity factor demonstrated is 247.7. The next step is to use this method on real data. For the purpose of this analysis, only the major activities are put under complexity analysis. These make up 90% of all wing box assembly activities.

5.2.3 Data Population

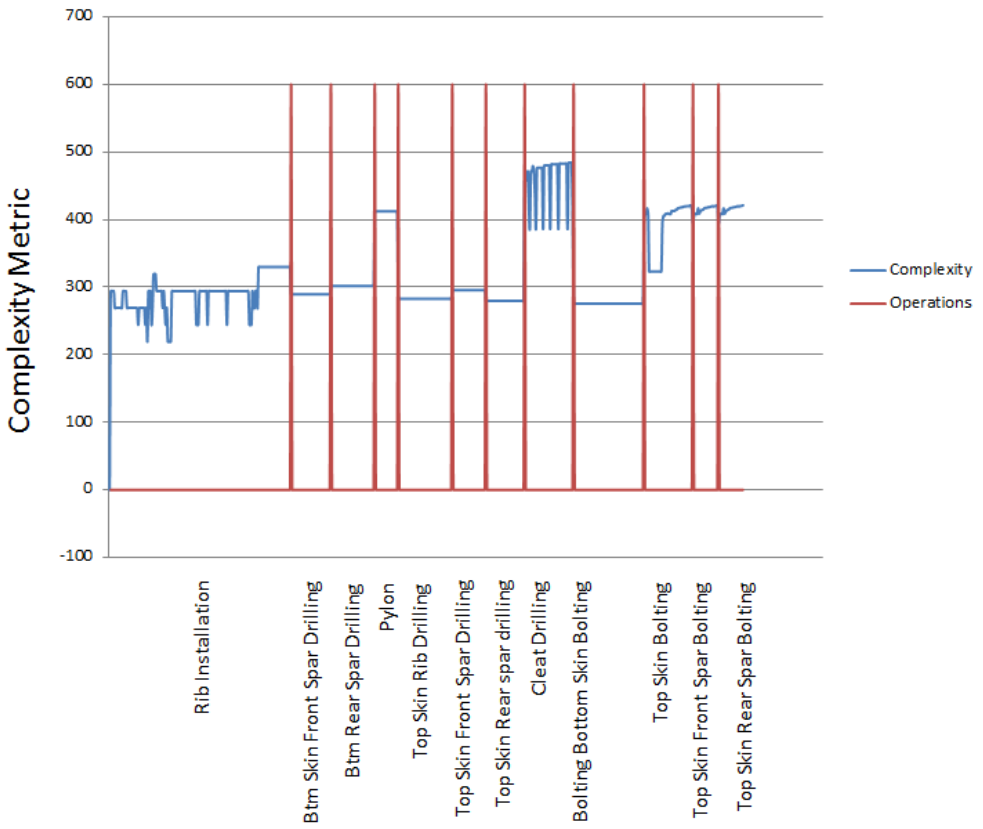


Figure 5-4 Showing Complexity data mapped out across the assembly activities

5.3 CASE STUDY ANALYSIS

The operations shown in Figure 5-4 are analysed in further detail in the following sections. A brief description of the operation and structural characteristics is provided, followed by some discussion.

5.3.1 Rib Installation

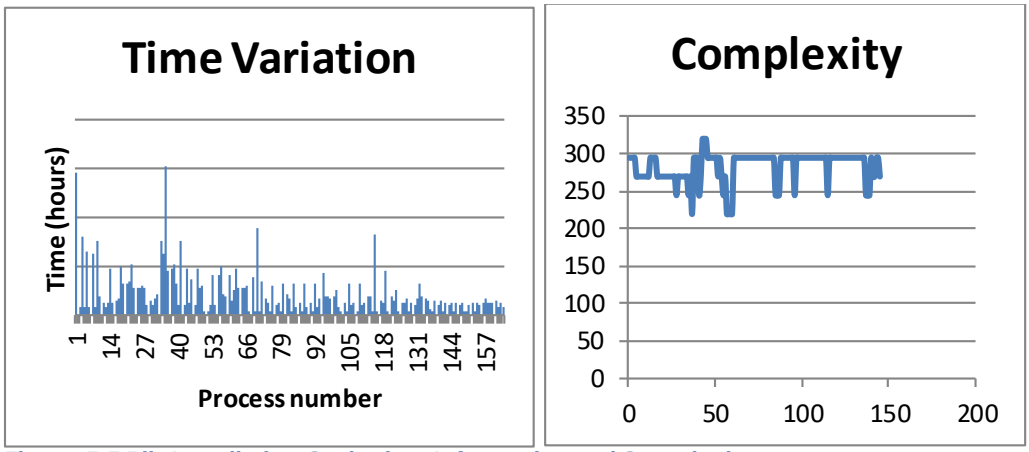


Figure 5-5 Rib Installation Cycle time Information and Complexity

Operation Description:

- Locate ribs to spars using tooling
- Drill and ream ribs to spars
- Remove ribs and clean
- Refit ribs and final bolt
- Fit support tooling onto certain ribs

Structure Characteristics:

- Two interfaces: Rib onto front spar, Rib onto Rear Spar
- Interfaces require tooling to locate
- Component volume can be manually handled in most instances but bulk of components makes handling more difficult.

Discussion:

The complexity of this operation varies depending on which rib the operation is being carried out on. Some ribs have an extra interface of another components that acts as a support bridge between two ribs and this adds further complexity to

the operation. Also noteworthy is that there is a downward trend in cycle time. This is related to the size of the components. As the size of the components gets smaller it generally takes less time to carry out installation activities.

As was discussed earlier, component size was not included as a complexity indicator.

There are some areas of constant levels of complexity and some sharp drops in complexity. Generally, the rib installation process is of lower complexity when compared with other processes. This can be observed in Figure 5-4.

Proposed Conclusions:

- Size of the components may correlate to high complexity.
- Multiple Interfaces increase complexity.

5.3.2 Bottom Skin Drilling

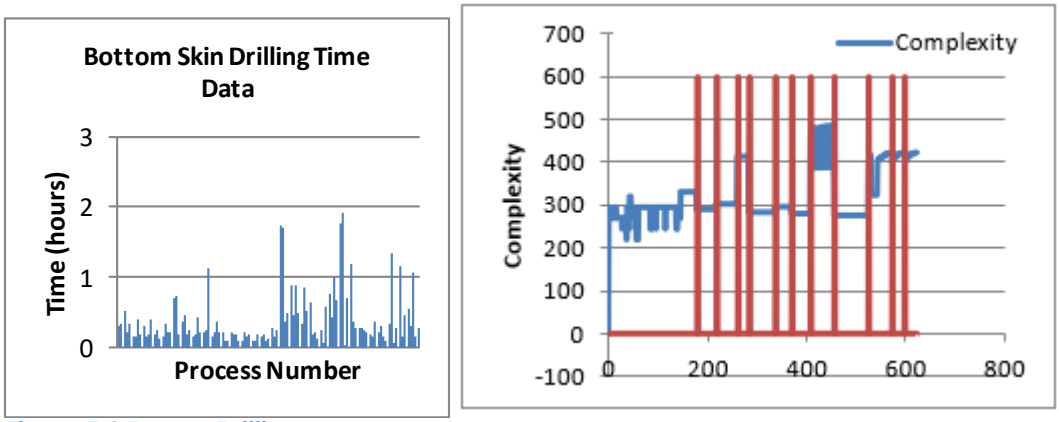


Figure 5-6 Bottom Drilling

Operation Description:

- Locate Drilling template
- Drill temporary fastener holes and install temporary fasteners

- Drill off and cold work remaining holes
- Remove drilling templates, insert temporary fasteners and manually drill out datum holes.

Structure Characteristics:

- Single Interface: Skin to Spar.
- Location carried out through the use of tooling drill jigs.
- Open space for operators to work

Discussion:

Three different operations are taking place under this banner. They are Skin to Front Spar drilling, Skin to Rear Spar drilling and Skin to Rib drilling. A relatively low level of complexity is indicated by the tool for all three operations. The complexity that is shown is stable for each process although the tool indicates a higher level of complexity for spar drilling. This is due to the use of thick template location which is not needed for Skin to Rib drilling. Rear Spar drilling is shown to be more complex than Front spar drilling. This is perhaps due to the irregular hole patterns that appear on the rear spar.

There are a number of factors that contribute to the consistent stability for each process. The first is that the working space remains consistent throughout the whole operation. The second is that all these operations take place in an open space. Also there are no barriers blocking the operators view from carrying out their activities. The only constantly varying factor is the time allocation. The time allocations shown in Figure 5-6 are characterised by regular spikes. These spikes correspond to where tooling, in the form of drilling templates, is located onto the structure. In the Rear Spar drilling process, there are more instances where

tooling location is required and this is represented by the slightly higher complexity.

5.3.3 Pylon Reinforcement Plate Assembly

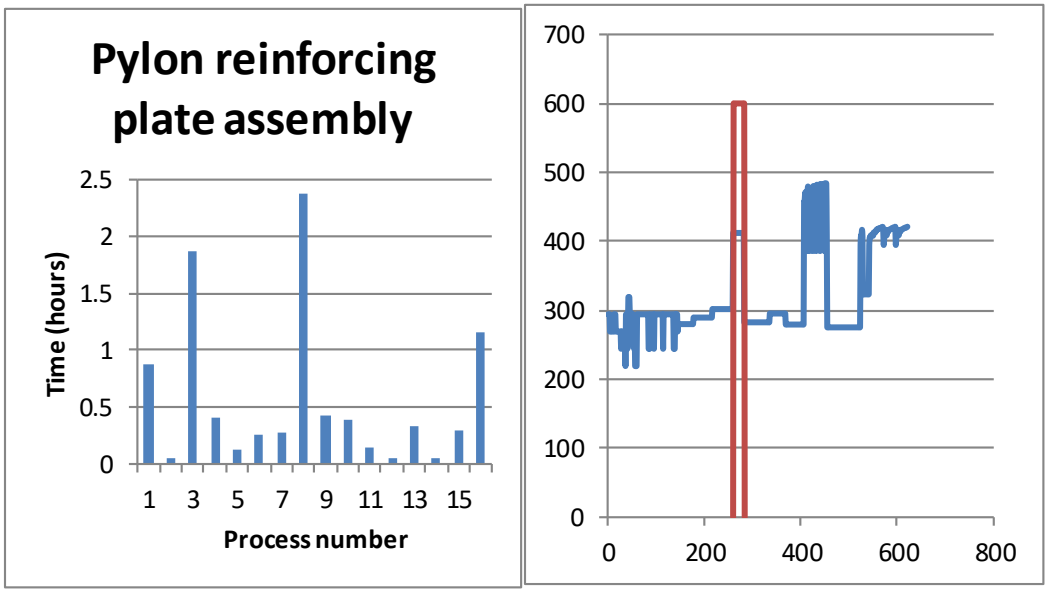


Figure 5-7 Pylon Reinforcing Plate Assembly

Operation description:

- Locate and clamp reinforcing plate
- Drill Pilot holes
- Use temporary fasteners to secure reinforcing plate
- Progressively drill remaining holes
- Back spot face
- Remove Temporary Pin from pylon forks and install solid pin
- Centralise heavy drilling jig using pylon forks and clamp
- Progressively drill large holes
- Remove heavy drill jig and install another drill jig by locating using the pylon monocle

- Progressively drill reinforcing plate into pylon
- Remove drill jig and locate A-frame to accommodate rack feed drill and drill holes
- Locate milling fixture onto A-Frame
- Mill reinforcing plate.

Note: “A frame” is a fixture that locates onto the structure using the pylon forks. It enables the drilling of large holes through a rack feed drill. It also allows the location of another fixture for milling.

Structure Characteristics:

- Pylon manufactured from Titanium. Higher strength and more difficult to machine then aluminium.
- High number of temporary fasteners required to locate components together due to the high strength of material.
- Multiple interfaces due to several components interfacing together. Components include wing cover, pylon and reinforcement plate

Discussion:

A high complexity value is indicated for this process. From the operation description, the sheer variety of activities is a contribution to the high complexity. There is little repetition in activity and thus there is little relationship between the time allocations for each activity. The other major contributing factor towards a high complexity is the nature of the material; titanium. Drilling, machining and even location of titanium is more difficult due to its increased hardness and

strength. Also, the requirement for operators to access both sides of the work piece further adds to the complexity.

Although the complexity indicated is stable throughout the process, this is likely because of the relatively short cycle time for this process, thus the time allocation average difference does not have a significant impact on the complexity stability.

5.3.4 Top Skin Drilling

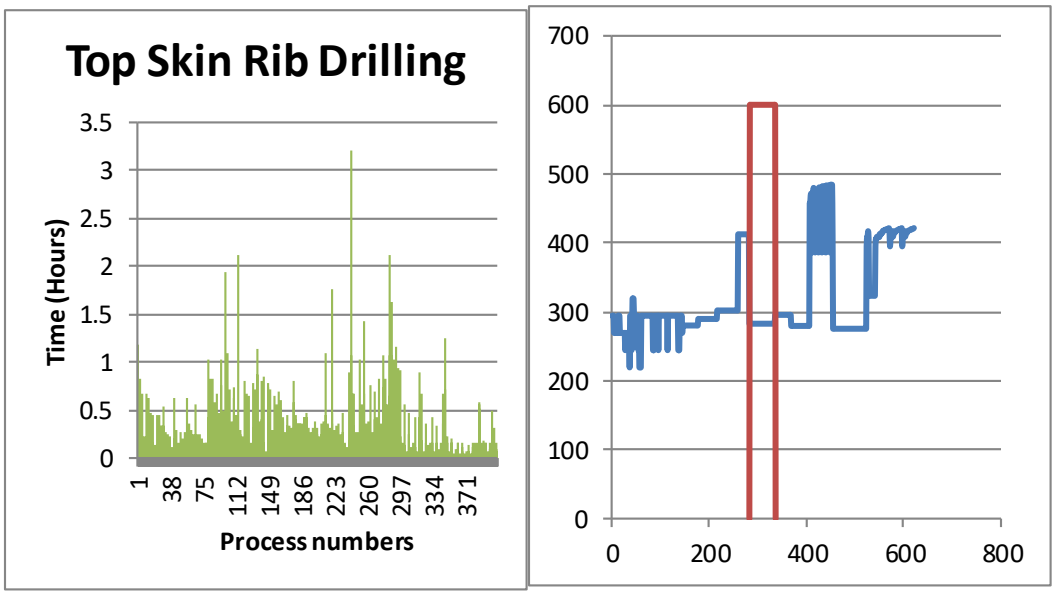


Figure 5-8 Showing data for Top Skin Drilling

Operation Description:

- Using specialised semi-automatic drilling unit, drill through drilling templates.
- Remove drilling templates and temporary fasteners.
- Apply temporary fasteners and use drilling equipment to open up pilot holes to final size

Structure Characteristics:

- Single Interface: Skin to Ribs/Spars

- Location carried out through the use of drilling templates.
- Open space for operators to work.

Discussion:

As with the bottom skin drilling analysis, the Top Skin drilling activities are grouped together and shown in Figure 5-8. Complexity for rib installation is slightly lower than spar drilling operations because drilling templates are installed as part of a different operation. Drilling templates are a form of tooling that allows an operator to manually position a drilling machine accurately This potentially lends itself to the idea that operations with large time allocations that have cyclic processes should be stream lined to remove all non-cyclic activities. Cyclic processes are those processes that involve a large amount of repetition. Non-cyclic processes are those that are made up of a number of unique activities. If those non-cyclic processes such as template or tooling installation can be carried out in other work packages that are generally non-cyclic this would enable complexity reduction in that particular area.

5.3.5 Cleat Drilling

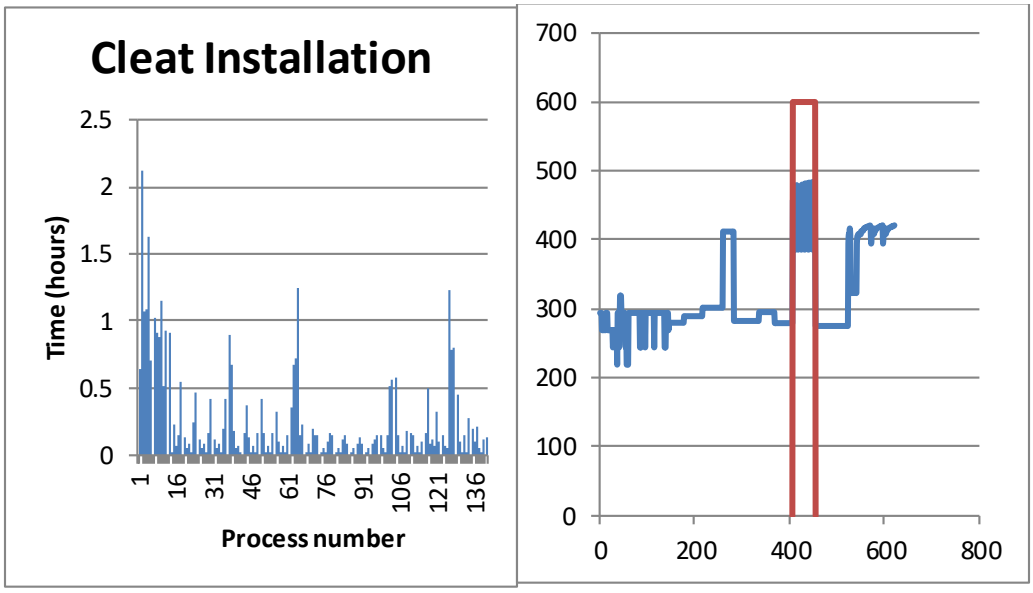


Figure 5-9 Complexity data for cleat installation

Operation Description:

- Measure position and locate cleats to stringers and ribs
- Progressively drill and clamp cleat, stringer and rib interfaces.
- Remove clean and store cleats

Structure Characteristics:

- Variation in cleat sizes
- Working space reduces, due to inbox working, as the work moves towards the wing tip

Operation Characteristics:

- Manual progressive Drilling
- Occasional requirement to fettle cleats for fitting

Discussion

As can be observed the complexity metric is not stable for this operation. Variation in the number of components at each rib bay causes this complexity variation. Generally, the complexity is high, even the troughs shown in the data are still significantly higher than the overall average complexity of this manufacturing system 324. As well as the variation in the number of components, each activity takes places in areas that have restricted access. Also components are required to be located onto a number of interfaces. Finally, there is variation in the size of the components being assembled, meaning that common tooling cannot be implemented. All operations are manually located and installed. All of these factors contribute to the high complexity.

5.3.6 Bolting Bottom Skin

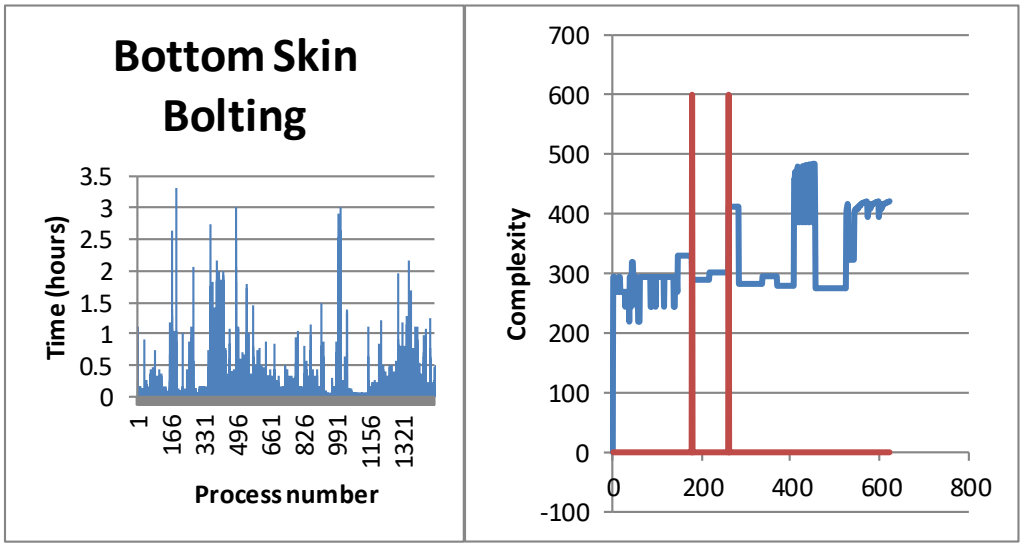


Figure 5-10 Showing Data for Bottom Skin Bolting

Operation Description:

- Check hole depth
- Apply sealant to bolt

- Insert in bolt
- Drive in bolt, whilst supporting from blind side
- Remove excess sealant
- Torque nut
- Check countersink depth and tail protrusion

Structure characteristics:

- Skin panels are large flexible aluminium sheets
- Skin Panels are given a shape through a forming process and through the assembly of structural stiffeners that run from root to tip.
- There are interfaces with all ribs and spars

Discussion

Bolting activities on the Bottom Skin have a relatively low complexity metric. There is no variation between bolting of different components such as skin to spar or skin to rib. Interestingly the time allocations for the activities involved are relatively high on average. This is due to the high number of steps for each activity. However, those steps are repeated numerously and thus the complexity is reduced. Also, there are no limitations on access despite the process requiring an operator on either side of the work piece.

5.3.7 Top Skin Bolting

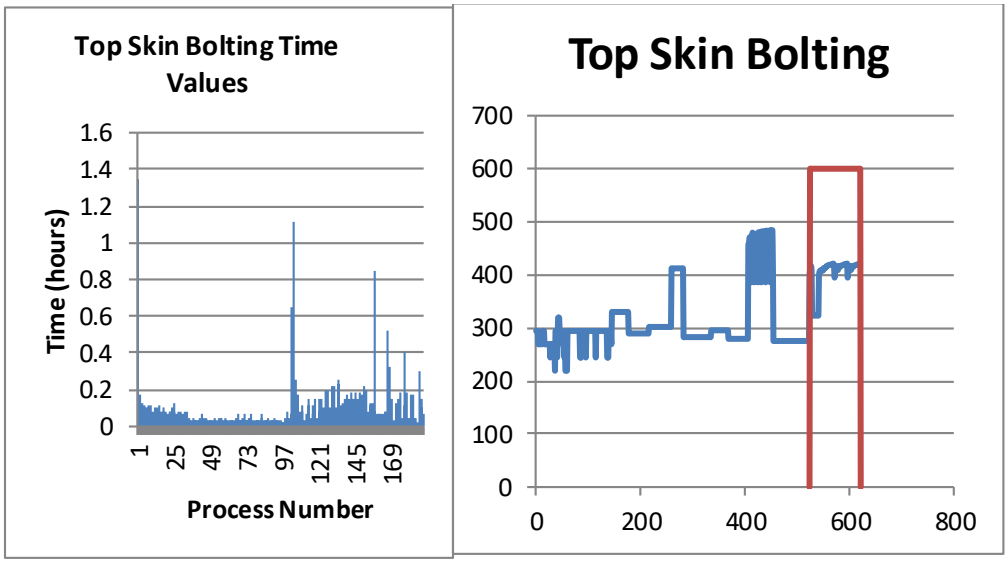


Figure 5-11 Showing Data for Top Skin Bolting

Operation Description:

- Check hole depth
- Apply sealant to bolt
- Insert in bolt
- Drive in bolt, whilst supporting from blind side
- Remove excess sealant
- Torque nut
- Check countersink depth and tail protrusion

Structure characteristics:

- Skin panels are large flexible aluminium sheets
- Skin Panels are given a shape through a forming process and through the assembly of structural stiffeners that run from root to tip.
- They interface with all ribs and spars

Discussion

The complexity values for the bolting of the top skin are higher than that of the bottom skin. The main reason for this is that access to both sides of the work piece is restricted as the bottom skin is now permanently attached and this means operators are required to carry out their activities in confined spaces. The varying available space for the operators is the reason that the complexity varies drastically. Drops in complexity can be observed when more space is available due to the absence of rib bays with seal plates or cross ribs.

5.4 TOOL DISCUSSION

The tool demonstrates areas where there are constant levels of complexity and areas where complexity varies. It is believed that these areas can be categorised into cyclic and non-cyclic processes. It is proposed that an area with stable complexity is a cyclic process and areas of variable complexity are non-cyclic. This is shown below in Table 5-5.

Stable Complexity	**Variable Complexity**
Bottom Skin Front spar drilling	Rib Installation
Bottom Skin Rear Spar Drilling	Cleat Drilling
Pylon	Top Skin Bolting
Top Skin Rib Drilling	
Top Skin Front Spar drilling	
Top Skin Rear Spar Drilling	
Bottom Skin Bolting	

Table 5-5 Showing areas of stable complexity and non stable complexity

There is an anomaly and this is Pylon assembly. This is a non-cyclic process but it has a stable complexity. This is perhaps due to the relatively short total allocated time. Every step of the process is of a high complexity and thus it appears as stable. As mentioned earlier, although Top Skin bolting appears to be very similar in nature to other bolting operations that are cyclic, the variable space working inside the wing box increases its complexity and also turns it into a non-cyclic process.

It was previously stated that cyclic processes were areas potentially ripe for automation. Historically this has been key to deciding which operations should be automated. Looking at the processes that have been identified as cyclic through this analysis, some, such as mass drilling operations are processes that have been automated in other applications and that technology is known to exist. Others such as the bolting operations are more difficult to automate due to several differences such as the requirement to access the hole from both sides of the work piece and the scenario of closed box working. However both these operations impact the same area and operate in the same vector. Although likely necessary at the time, perhaps a design that can limit the non-cyclic element is beneficial.

The operation with one of the lowest complexity scores is that of Top Skin Rib Drilling. One of the reasons behind this is that the tooling location is not part of that operation and is carried out separately. This is a key contributor in raising complexity in other mass drilling operations. It is clear that balancing activities within packages of work can lead to more efficient production and the removal of non-direct value adding activities, such as tooling location, is desirable. Perhaps

introducing a design criteria of “cyclic filtering” is beneficial. Cyclic filtering is the process by which cyclic processes are streamlined so that complexity adding activities are moved into other activities that are non-cyclic or preferably removed altogether. As demonstrated by this complexity analysis, cyclic activities have lower complexity, indeed, discussions with the Manufacturing Engineering teams on the three non-cyclic activities listed here indicate that these processes suffer from failures such as misalignment and rework far more than the cyclic activities.

5.4.1 Conclusions

This Chapter presented a new complexity analysis tool this is specific to the aerospace manufacturing sector. The novelty of this complexity tool is in the fact that it considers the intricacies of what will drive the manufacturing system. These factors are what can create bottle necks or high cost areas. Further, no complexity analysis tool captures the whole manufacturing system in using a macro view such as is presented here. As was demonstrated, this provides great insight at development stage and also at redesign stage. In Chapter 7 a detailed validation of this is presented.

The next Chapter will discuss how aspects of this kind of macro complexity analysis can be incorporated into technology development planning.

6. SHARED PLATFORM APPROACH

6.1 INTRODUCTION

Chapter 4 proposed the use of a Redesign for Assembly comparison tool to identify areas ripe for optimisation through redesign or technology insertion. Chapter 5 proposed the use of a complexity metric that could provide a macro view of a production system and could offer suggestions as to improvement areas. Whilst this method was demonstrated and validated on an existing assembly there is greater value in its use at the development stage. During this stage, engineers frequently carry out simulations on the nature of production systems. This usually takes place in the form of cost studies such as cycle time estimation, digital simulation using CAD, manufacturing technology cost and footprint assessment and component manufacturability assessment. This approach is particularly successful in shorter life products. In the case of long life products such as aircraft it was observed in Chapter 0 that a different approach is valuable. As has been mentioned previously, aircraft manufacturers traditionally favour redesign of components for performance optimisation and the difficulty in implementing redesign for assembly projects was discussed. Technology insertion was the preferred option so as not to risk compromising the performance and the quality of the product mid-life. It therefore seems prudent during the development stage to adopt an approach that acknowledges this fact. It is also observed that the assembly product, in this case, a wing is held in a particular orientation during production. This orientation does not change often due to the size of the component and also to avoid the risk of compromising the high accuracy assembly before it is in stable condition. Thus many assembly operations take place in the same vectors. The significance of this and elements similar to this is explored in more detail within this chapter. In this chapter, an

approach to manufacturing system development is proposed that is holistic in considering technology future implementation and also in simplifying manufacturability.

The chapter begins by discussing what is meant by Shared Platform Approach and also by putting forward a proposal as to what objective is to be achieved in this area. The chapter then discusses the factors that need to be explored in over investment justification including cost estimation and technology maturity. A methodology for shared platform approach is then proposed and demonstrated on one application within aerospace assembly. A case study of the methodology is then presented and validation of the methodology is demonstrated. Finally, detailed examples of how shared platform approach can be applied for future product development are demonstrated.

6.1.1 What is Shared Platform Approach

Shared Platform Approach is the idea that development of manufacturing systems is done in a way that minimises the future investment. The following are scenarios of such a proposal:

- Development of products that enable the use of common location technology, therefore reducing investment cost in the future.
- Design for Assembly to enable common technology utilisation.
- Early Identification of problem areas and future technology strategy.

From the operations discussed in Chapter 5, there are many operations that take place in the same vector. For example, in aircraft assembly, a large proportion of the work that takes place is related to drilling. However, the nature of those drilling operations is vastly different. Some areas such as the Pylon and the Gear

Rib require tools capable of machining titanium, whereas there are many different sizes of holes. There is specialised equipment for different applications. The approach to automation is to typically identify an area of high repetition and develop a system to meet the needs of that area. Usually, a minimalist approach is adopted; this is, that the minimum amount of investment is made in order to achieve a proposed outcome. Shared Platform approach would allow justification of more capable technology investment in order to satisfy a future need.
The complexity analysis in Chapter 4 enables the engineer to predict areas of low complexity and high repeatability. This enables the engineer to identify activities that take place in similar vectors and also influence design to enable more activities to take place within common vectors.

6.1.2 Proposal

As mentioned in Chapter 5 there are inevitably cyclic operations that operate in the same vector. Designing areas with common feature characteristics allows for a shared platform approach. For example, if there is a design or a technology enablement that could allow single direction application on surface bolting operations then this will open the door to shared platform technologies for both bolting and drilling of covers to other structures. Shared platform approach is sharing technology for multiple applications. It is not the use of the same technology that can carry out multiple operations. Whilst single technology, multiple application, such as a multi tool end effector is powerful technology, it limits flexibility for the use of newly developed technology. This is particularly important for long life products that are likely to remain in production through several technology advancements. Shared platform approach allows economic investment in technology whilst still allowing for flexibility. For example, the same robot arm, with the same repeatability and accuracy capability will be required for

both bolting and drilling applications. Robot sets need only be purchased once with specific end effectors developed and purchased for each application. Even if drilling and bolting take place in different assembly stations and the technology is required in multiple stations, shared platform approach reduces the cost of those robots by standardising them. It also allows suppliers to work and develop technology for a known platform and this reduces the cost of being competitive for suppliers.

In this study it was also shown that complexity correlates to non-cyclic processes. Achieving cyclic processes reduces risk of error and increases quality as well as increasing potential for automation, if that is a requirement.

Complexity analysis allows an engineer to demonstrate where key complexity bottle necks can be eliminated. The correlation between non cyclic processes and complexity indicates that an approach to DFMA for either redesign or new product introduction should aim to eliminate complexity factors whilst introducing a common platform approach. Working volume is particularly interesting in this regard. Where ever working volume is reduced, a process becomes more complex because of limited space access and limited visibility. In the operations that have been analysed this includes bolting of top skin panels. If large and direct research investment is applied to achieve a single sided bolt this would eliminate closed box working in this area as well as introduce the potential for a single platform approach with drilling.

Introducing a shared platform approach, such as a common robot arm that can use different end effectors will require investment in the common platform above

what would be required for a single application platform. This is demonstrated in Table 6-1.

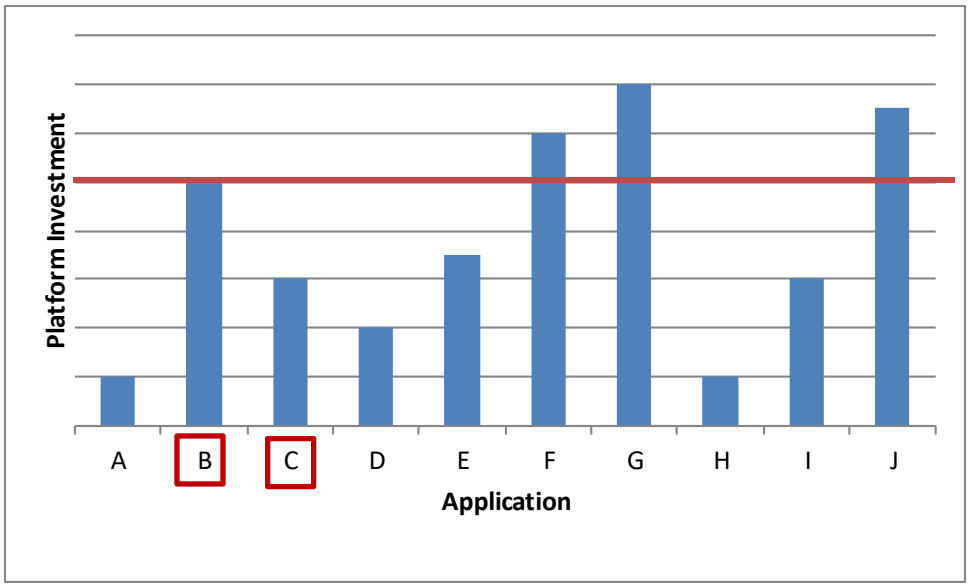


Table 6-1 Demonstrating Common Platform investment requirements

If for example, applications A-J operate in similar vectors and targeted design for assembly projects enable them to share a platform, then an over investment to cover application B will provide a technology platform for application C. However, the argument against this kind of investment would be severe if the end effector on application C was a mature technology and application B was not mature. The question to be answered is how can a theoretical justification be made for the larger investment? Also, if there are a wide number of applications that can share a platform where is the line drawn as to how many applications should be included?

6.1.3 Justifying over investment

The answer to these questions is multi-faceted. It involves taking into account the following:

- Technology maturity
- Cost estimation of technology solutions

- Cost mitigation analysis for over investment opportunities.

These are further discussed in the following sections.

6.1.4 Technology Maturity

Technology maturity is typically assessed through the use of maturity gates (Chan et al., 2000). This method was pioneered by the National Aeronautics and Space Administration (NASA) in the 1960's. The technology readiness level scale was originally developed as a 9 stage classification, ranging from "basic principles observed and reported" to "system implementation." Table 6-2 demonstrates this:

TRL	Definition	Description
1	Basic principles observed and reported.	Basic scientific research has evolved into an observation and reporting of basic principles suited to transfer into applied research and development.
2	Technology concept and/or application formulated.	Practical applications are applied of invented for the basic principles defined previously.
3	Analytical and experimental critical function and/or characteristic proof-of-concept.	Activation of research and development within the appropriate environment to physically validate the proof of concept for the application.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological parameters of the development must be integrated to evaluate whether they function and attain the concept performance requirements at the level of component and/or breadboard.
5	Component and/or breadboard validation in relevant environment.	Basic technological elements must be integrated with other supporting developments and tested in a realistic environment.
6	System/sub-system model or prototype demonstration in a relevant environment.	A full scale prototype system or system must be tested in a relevant environment, typically space. This demonstration will typically have many technologies integrated.
7	System prototype demonstration in the expected operational environment.	An actual system prototype is required and demonstrated in the aligned operational environment. The prototype should be near or at full scale.
8	Actual system completed and 'qualified' through test and demonstration.	This is the end of the development for most technologies applied to the system. This can also involve addition of a new technology to an already developed system.
9	Actual system 'flight proven' through successful mission operations.	All technologies being developed and applied to the system progress through TRL9. However, the refinement and bug fixing of the system are not defined until the final launch of the system. This forms the definition of TRL9.

Table 6-2 Technology Readiness Level Definitions (Mankins, 2009, Jones, 2014)

This approach has been adapted in a number of forms such as Manufacturing Capability Readiness Levels (Ward et al., 2011) and Manufacturing Readiness

Levels MRL's (Department of Defence, 2011). At development stage, technology is in the range of TRL 1-6. Post TRL 6 is implementation stage. The first question to be answered on TRL is as follows:

"At what technology maturity does a technology become viable for consideration into future investment?"

The following discussion of each TRL stage can contribute in answering this question:

Table 6-3 Discussion of each TRL stage. Aided by Airbus, 2011.

TRL	Discussion
1	At this level, a project or problem has been identified. There has been no development or solution proposed. There is no opportunity to justify a cost at this stage.
2	A low level invention is proposed but only theoretical data provides support. Risk is still too great to justify an expenditure.
3	Principals are demonstrated and analysed and applicable data has been generated in support of a concept. There is the potential for an argument to be made for a minimal investment in a shared platform for the potential that is offered.
4	All aspects are demonstrated under laboratory environment. Solution is mature enough to function under controlled conditions and at this point a strong case can be made for mitigation of risk against the opportunity that an investment may provide.
5	All aspects demonstrated under real environment. This is close to being a mature technology and the likelihood is that a technology at this stage would be considered for implementation in a development product despite not being at total maturity.
6	Mature Technology; can be justified using traditional method of business case application for capital expenditure.

In **Error! Reference source not found.** the author discusses how TRL maturity relates to cost justification. The middle TRL levels are those that are most relevant for shared platform approach. From **Error! Reference source not**

found., there is a clear sliding risk scale. The higher the TRL maturity the lower the risk to successful technology deployment.

It would be remiss of a company to reach the higher maturity levels in process optimisation for manufacturing activities on multiple applications that share some similarities and not look at saving cost through combining features. It is in the middle TRL;s such as 3 and 4 that there is an opportunity for this to be exploited. This is the stage where a problem has been identified and a certain amount of work has already taken place in creating solutions. At this stage a cost mitigation exercise for justification is beneficial. In this area a technology is in development but the full scale of its impact is not fully known. There is still a significant portion of risk however, coupled with the risk is a clear opportunity. Typically, if the opportunity is greater than the risk, then in a regular development program, investment will be made to progress it to the next maturity level. This will continue until either the technology is fully realised and then adopted or until a factor emerges in the technology that prevents it from being adopted or further matured. At this stage, the size of the opportunity will play a vital part in the pursuit of an investment justification.

6.1.5 Cost Estimation

There is a substantial body of work on cost estimation that has been previously discussed in section 2.8. The aim of this research is not to develop a unique cost estimation tool rather it is to develop a justification method for over investment at development stage. As such, a method for estimating the future cost of a currently low maturity technology is needed. From section 2.8, the most appropriate method appears to be a combination of the Analogous method and the Parametric method. From the existing tool sets, the ones developed by Boeing R&T and NASA, P-Beat has a relevancy due to the similar drivers that are

used to form its cost estimation relationships (CER). It is proposed that a similar approach should be taken using the complexity metric for processes derived in chapter 4, technology maturity and design maturity. As stated previously, the aim of this research is not to develop a unique cost estimation tool, rather it is to develop a shared platform approach strategy.

6.2 PROPOSED METHODOLOGY

Cost estimation and technology maturity are the two critical aspects in justifying investment. The previous section discussed which aspects of those areas are relevant in the context of shared platform approach. A methodology is now needed to utilise those aspects in providing a positive shared platform approach result.

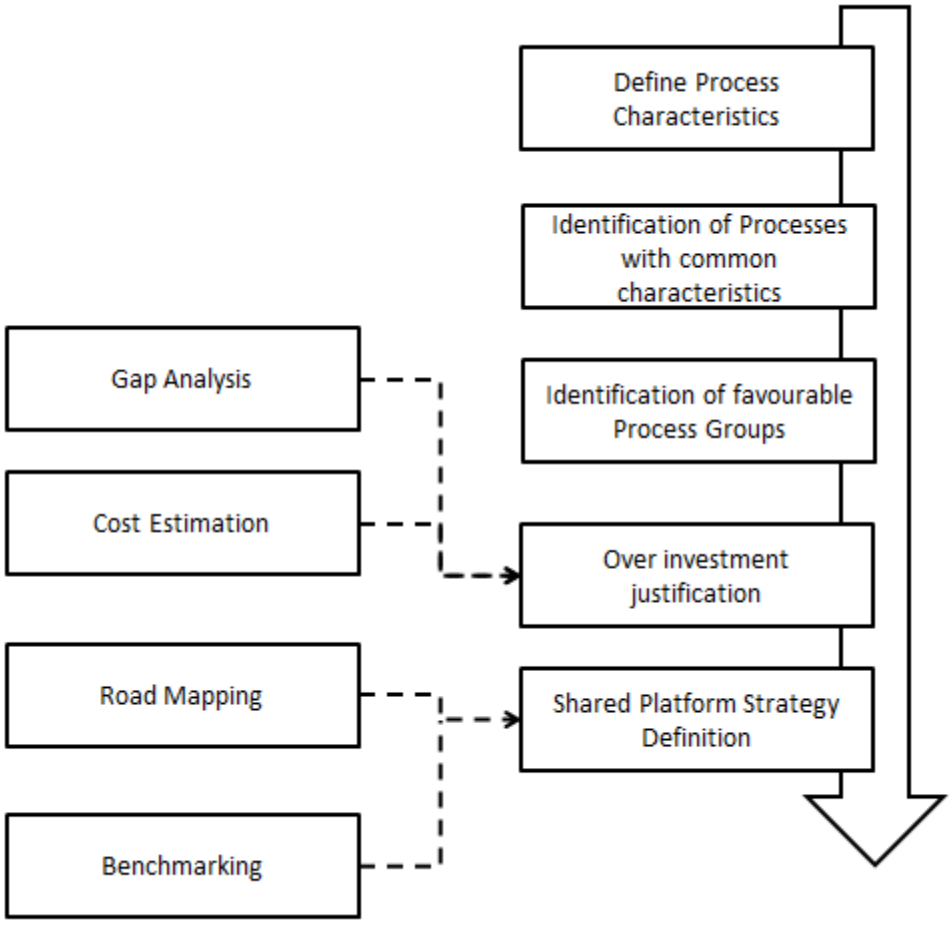


Figure 6-1 Methodology for adoption of a Shared Platform Approach\

Define Process Characteristics: The first step in this method is to identify characteristics of the processes within the manufacturing system. It is important to identify characteristics that can be compared together. The characteristics will usually be independent of technology, encompassing aspects such as motion

direction or force requirements for assembly. These characteristics are the components that make up the intrinsic nature of the manufacturing system.

Identification of Processes with common characteristics: This stage is an analysis where every process within the manufacturing system is compared against each other and thus identifying which processes have high or low commonality.

Identification of favourable process groups: This stage involves defining what constitutes favourability when contrasting processes. For example, if the key is to enable assembly cycle time reduction through implementation of automated technology, then cycle time becomes the key impact assessment. Once the metric for favourability is established, process groups or pairs can be assessed to identify the most interesting combinations.

Overinvestment justification: There are two elements to justifying an overinvestment. Ultimately the aim is the use of cost estimation tools to predict development cost of technology. However, as there are many processes being compared against each other, the analysis would be time consuming. This is especially since cost estimation of technology development requires direction, meaning that the beneficial technology is identified for each process. To limit the breadth of this analysis, a method to measure the gap between processes is proposed. This will enable the engineer to make a rapid assessment on the costs involved in bridging a gap between two processes to enable them for a shared platform scenario. If a gap metric indicates that the cost of implementing a shared platform between two processes is high then the justification will depend on the combined impact of those two processes.

Shared Platform strategy Definition: This is the final step. After process groups are identified from an impact perspective and the bridging cost is assessed, this stage sets out the strategy to achieve a shared platform situation. As the process groups are now identified, detailed benchmarking and technology road mapping will take place.

6.3 AEROSPACE ASSEMBLY APPLICATION

The general methodology outlined in Section 6.2 is now implemented for the case of the assembly of a wing box structure. This is the same wing box manufacturing system that has been the focus of this research in previous chapters and is outlined in detail in section 3.2.1 (page 50).

6.3.1 Define Process Characteristics

For this scenario, it is important to identify characteristics that are technology independent. In this case these are generally motion characteristics. These differ from those characteristics mentioned in Chapters 4 and 5. These characteristics relate to the motion involved when carrying out a process. These are identified and discussed in **Error! Reference source not found.** below:

Table 6-4 Showing motion characteristics

Motion Characteristic	Explanation
Direction of Motion	This the direction in which the one end effector moves. For example, if a drilling operation takes place on a vertical skin panel this would be considered as taking place in the x direction. Variations in angle are expected. This is more an indication of the general direction in which a platform is required to be manipulated
Positional Accuracy Required	This is the accuracy that a platform is required to position its end effector into.
Force Requirement	This represents the forces that are required to either be delivered or reacted against during the process
Payload Capacity	This is the weight of the end effector that a platform is required to bear

An exercise in modifying design to create more processes with similar characteristics is an important outcome of this step. For example, bolting and drilling both take place in the same direction. However, bolting has a requirement for torque application to attach a nut. In the design of the bolt and the assembly, there is no opportunity of using the same platform for drilling as bolting without introducing a single robot on the other side. This is not inconceivable but a more efficient solution may be to modify the design of the assembly so that the same robot can provide a platform for two different end effectors to carry out their processes.

There is no indication as to which direction the motion is travelling in. This is because the motion takes place in a direction depending on which work piece is being operated on. For example, the bottom and top skin will have similar drilling operations taking place, but due to those components being on either side of the

wing structure, the motions for carrying out those drilling processes will be opposite.

6.3.2 Identification of Processes with Common Characteristics

This stage groups together processes that have similar motion characteristics. This enables identification of operations that are able to share a platform. At this stage, processes are selected based on their impact on the assembly. Impact for this application is identified as assembly cycle time.

For example, a small task that shares many similarities with a larger, time consuming task and is likely to have the capacity to share a platform with such a task would likely not be selected for further consideration based on the limited potential for future payback on an over investment at design stage. However, two processes that have a significant impact and have less characteristics in common should be selected for consideration and derivation of a shared platform strategy. A shared platform strategy is where changes are made to the design of the assembly or components to accommodate a single platform for high impact processes.

6.3.3 Identification of Favourable Process Groups

Process group categorisations are identified below in Figure 6-2.

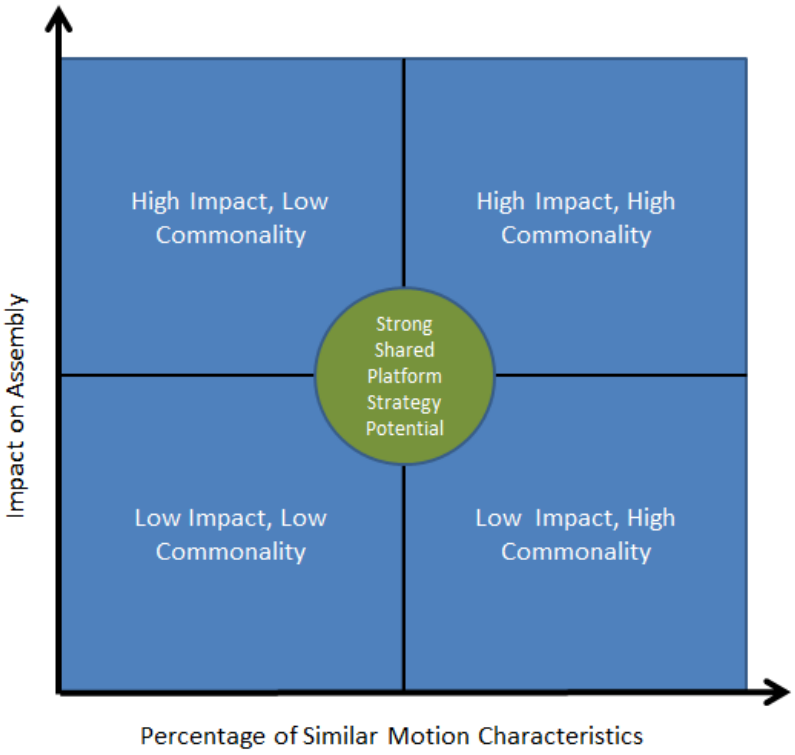


Figure 6-2 Demonstration of where shared platform approach is most appropriate.

The axis shown in Figure 6-2 are impact and percentage of similar motion characteristics. The X-Axis is demonstrating commonality and is an indicator about whether a shared platform strategy is likely.

Impact is defined as a combination of overall assembly time and the potential cost to automate. It is related to the complexity of the operation. It is the impact total, where the impact of multiple processes is combined, that is the main indicator as to whether there is any benefit in combining operations.

- *High Impact, Low Commonality:* These are processes that have a high impact total but have very little common motion characteristics. These operations are unlikely to be considered for a shared platform strategy due to the likelihood that design modifications to create motion commonality are likely to be too challenging to accommodate.

From Figure 6-2, the following scenarios are visible:

- *High Impact, High Commonality:* These are processes that share many motion characteristics and have a high impact total. Processes that fall within this category should be considered for shared platform approach in their current form. Minimal design changes would need to be carried out to enable this.
- *Low Impact, Low Commonality:* Processes that fall within this category will not be considered for shared platform approach.
- *Low Impact, High Commonality:* These are operations that have a high proportion of similar motion characteristics but the processes themselves sum together to offer a limited overall assembly and cost saving impact.
- *Strong Shared Platform Strategy Potential:* These are combinations of processes that could yield a strong cycle time impact where a shared platform approach strategy will need to be adopted. These are the operations that lie within the scope of design for assembly engineers.

There are 19 major operations that take place during the wing box assembly of this analysis. Each one of those is required to be compared against the other to identify which category they fall into. It is proposed that this is carried out using a "Gap" metric.

6.3.4 Over Investment Justification

There are two elements to justifying an over investment once a profitable shared platform scenario has been justified. The first is cost estimation and the second is a future business case. The literature review discusses in depth the current models and techniques that exist for cost estimation, it was highlighted that a method that takes into account both parametric and analogous methods, such as

the P-Beat method (Schankman and Reynolds, 2010), was the most useful in this scenario.

This method established cost relationships between technology and design maturity, resource capability and software and hardware complexity. In this case the complexity of the software and hardware complexity is driven by the process and product complexity. In Chapter 4, a method for deriving such a complexity was demonstrated. However, for the purpose of a shared platform analysis the complexity itself isn't sufficient as an indicator. It is proposed that the complexity factor is used to measure the "gap" between two processes. This is the difference between the technology requirements. It is proposed that this technology gap will provide an indicator for a method such as P-Beat to factor in. The gap between two processes also offers an indication as to the level of over investment required. This is further explored in the coming examples.

Technology maturity assessment has been mentioned in an earlier step of this method and design maturity takes place consistently during the product development cycle. Resource capability is slightly more complex and is split in to two for each element of product development and technology development. Resource capability can be established for technology development based on tacit knowledge created from historical relationships with suppliers. Resource capability of product development can be assumed to be high based on the industrial history of the manufacturer of the wing used in this scenario and also its shared dominance of the commercial aerospace market.

A gap metric is proposed. The gap metric for this application is derived using the characteristics of the processes already defined in section 6.3.1. They are translated into metrics that can be compared against each other and then a gap is

calculated through the difference between two processes. An example is shown below:

	Drilling Operation A	Drilling Operation B	Translation	
Complexity	412	290	7.067	3
Technology Maturity	3	9	3	9
Positional Accuracy Required (mm)	0.2	0.2	2	2
Force Requirement (N)	2500	7500	25	75
Payload Capacity (kg)	5	12	5	12
Total			42.07	101
Gap Metric	58.93333333			

Figure 6-3 showing the calculation of a Gap Metric between two arbitrary drilling operations.

The intention of the Gap metric is to provide an indication to the engineer as to the potential cost and effort involved in bringing two processes within each other's scope of reference to enable a shared platform application. This is demonstrated in Figure 6-4.

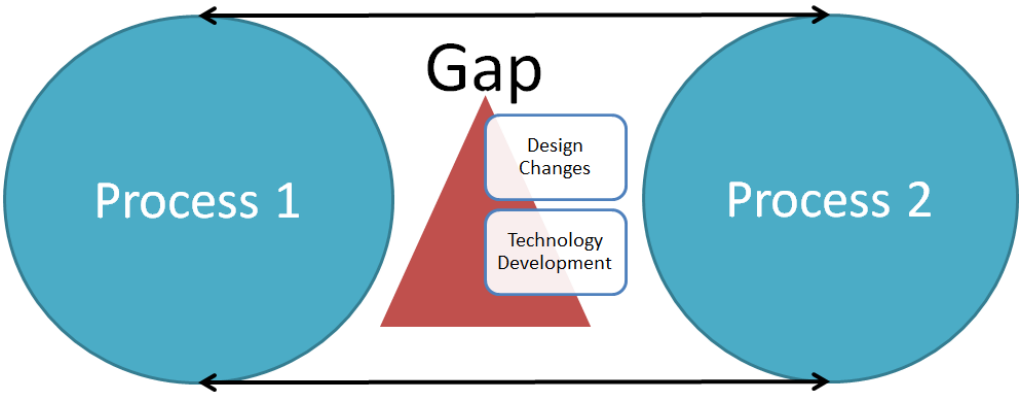


Figure 6-4 representation of the Gap metric

A translation calculation is used to bring the various factors into the same order of magnitude. This is demonstrated in the table below.

Table 6-5 Showing thre translation calculations to bring the factors into the same order of magnitude.

	Translation Calculation
Complexity	((Complexity-200)/300)*10
Technology Maturity	As is
Positional Accuracy Required (mm)	Multiplied by 10
Force Requirement (N)	Divide by 25
Payload Capacity (kg)	As is

6.3.5 Shared Platform Strategy Definition

This stage takes the processes identified in the previous stage and benchmarks the latest technology and processes applicable to those processes deemed significant. Of the processes that lie within the High Impact with high commonality segment, this is a technology benchmarking exercise with a maturity assessment. Existing technologies are assessed and if they are mature, are likely to be deployed in a competitive industrial environment. For those technologies that are not yet mature, they will require the next phase of this method: Over Investment Justification.

This is also the stage of the methodology where those processes that have been identified as needing a strategy definition are considered. The strategy definition involves asking two questions:

1. What design aspects need to change about a set of processes that allows them to share a platform with multiple processes?
2. What Technology would enable that and how can that technology be matured?

The maturity of the technology has a direct impact on development cost and this will be discussed further in the next section of the methodology.

As well as technology benchmarking, an exercise in technology road mapping is also required. Road mapping is essential for effective resource and budget allocation over a long period of time (Lee et al., 2007).

6.3.6 Shared Platform approach Decision

The final step of this method is to make a decision on whether to pursue the identified process groups. It is in this section that a decision is made on which

technologies are to be invested in for long term development and what over investments are made to support the implementation of those long term developments.

6.4 CASE STUDY

To verify whether the proposed method is useful it has been applied on the assembly of a wing box. The method is applied in a scenario of the development of a new wing. The data is gathered from an existing assembly.

Figure 6-5 shows the co-ordinate system used for the motion analysis carried out in this section. The direction of motion characteristic uses this co-ordinate system and it is the same co-ordinate system that a wing is typically designed in. The X direction follows the length of the wing span. The Y axis is the chord direction and the Z axis is the direction of the "thickness" of the wing.

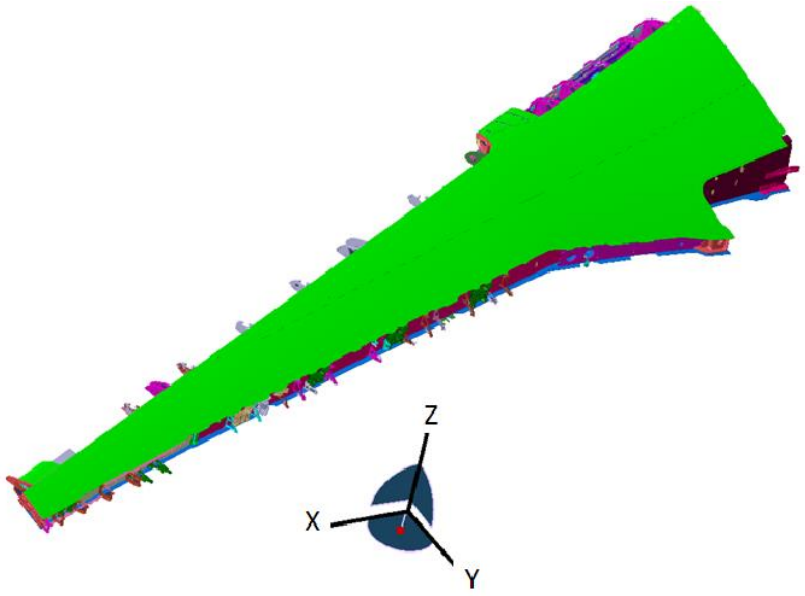


Figure 6-5 Aircraft Orientation

	Direction of Motion	Positional Accuracy Required (mm)	Force Application Requirement (N)	Payload (Kg)
Rib Location	Z	0.2	0	70
Rib Installation	X	5	100	5
Bottom Skin Location	XYZ	3	0	1500
Bottom Skin Rib Drilling	Z	0.2	100	5
Front Spar Drilling	Z	0.2	100	5

Rear Spar Drilling	Z	0.2	100	5
Removal of Bottom Skin	XYZ	0	0	1500
Pylon Drilling	Z	0.2	300	12
Locate top Skin	XYZ	3	0	1500
Drill Top Skin to Ribs	Z	0.2	100	5
Top skin front spar and rear spar and rib drilling	Z	0.2	100	5
Cleat drilling	XYZ	0.2	100	2
Remove Top skin and deburr	XYZ	0	0	1500
Bolt Bottom Skin	Z	0.2	50	3
Flap Track drilling and bolting	Z	0.2	100	5
Relocate Top Skin 1 and bolting	Z	0.2	0	1250
Relocate Top Skin 2	XYZ	3	0	1250
Top Skin Bolting	Z	0.2	50	3

Table 6-6 Showing Data Population for a commonality analysis for the major operations in wing assembly

6.4.1 Gap Metric

Figure 6-6 shows the gaps between the processes documented under this case study.

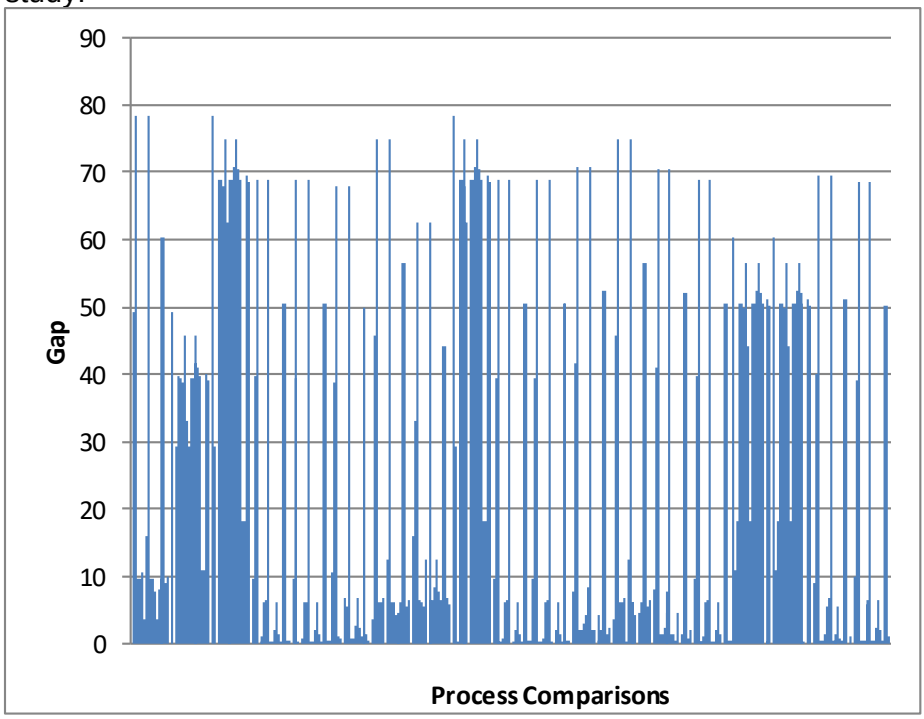


Figure 6-6 Showing a chart displaying the gaps between all processes in wing box assembly

6.4.2 Validation of Gap Metric

To validate the usefulness of this gap metric, five of the highest scores and five of the lowest scores are analysed to see whether they correlate with reality.

Table 6-7 Showing 5 of the lowest gap scores and their associated processes

Lowest Gaps		
Removal of Bottom Skin vs Remove Top skin and deburr	0.00033	These are near identical processes. If a technology is developed for one of these then it will definitely be applicable to both. Only minor changes will be required for Top and Bottom skins.
Bottom Skin Location vs Locate top Skin	0.0033	These are also near identical processes. Whatever is applicable on the top skin will be applicable on the bottom skin.
Drill Top Skin to Ribs vs Front Spar Drilling	0.0267	Both of these operations are structural drilling operations. Automated drilling has already been implemented that allows for a shared platform for both of these processes.

Bottom Skin Rib Drilling vs Top Skin Rib	0.0633	These are also structural drilling operations and share the same characteristics. However, the engineer should be vigilant in monitoring which components they address. Although the same technology would be able to carry out both of these processes, they do not occur in the same area.
Bottom Skin Rib Drilling vs Drill Top Skin to Ribs	0.0663	As above, this is structural drilling.

Table 6-8 Showing 5 of the highest gap scores and their associated processes

Highest Gaps		
Rib Location vs Bottom Skin Location	78.536	These processes share almost nothing in common. The weights of the skin components are of several orders of magnitudes different to the rib components. There is also a large difference in location accuracies.

Removal of Bottom Skin vs Bottom Skin Location	75.003	The vast gap metric given here is perhaps anomalous. There are some shared characteristics in these processes, such as the weight of the components. However, the differences are also great. No accuracy is required in removing the a skin, whereas location of a skin is a high accuracy operation. This is especially difficult due to the size of the component, its weight and its flexibility.
Cleat drilling vs Bottom Skin Location	70.903	Cleat Drilling is an almost unique process. Many of the highest gap metrics are those that are compared with clear drilling. Cleat drilling is at odds with the rest of the assembly due to the intricate nature of the work and this is displayed effectively by gap metric.
Top Skin Bolting vs Locate top Skin	69.503	These processes also share no commonality and thus add credibility to the gap metric
Bottom Skin Location vs Front Spar Drilling	68.906	As with the other processes with a high gap metric score,

		these processes share little commonality.

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Bottom Skin Location vs Front Spar Drilling	68.906	As with the other processes with a high gap metric score, these processes share little commonality.

discuss some of the highest and lowest scoring process pairs. The Gap metric provides a strong indication to process pairs that have high and low commonality. Anomalies can appear. In order to make the classifications discussed in Figure 6-2, impact is also required to be accounted for. For this analysis, impact is assessed according to cycle time.

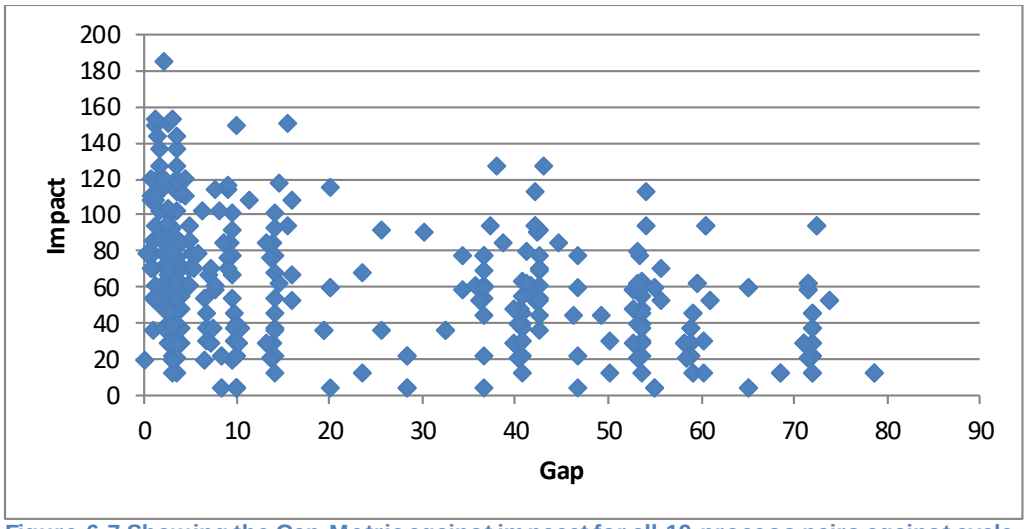


Figure 6-7 Showing the Gap Metric against impacct for all 19 process pairs against cycle time impact

Categorisations

The Tables below take representative samples from Figure 6-7. They are divided into the 4 categories that were listed previously in Figure 6-2.

Table 6-9 Identification of process pairs

High Impact Low Commonality
Rib Installation vs Bolt Bottom Skin
Relocate Top Skin 1 and bolting vs Bolt Bottom Skin
Relocate Top Skin 2 vs Bolt Bottom Skin
Bottom Skin Location vs Bolt Bottom Skin
Bolt Bottom Skin vs Bottom Skin Location

These are processes that are perhaps too different in nature and are unlikely to be able to share a platform with each other despite the attractiveness offered by their impact, as can be seen, the bolting of the bottom skin appears extensively in both **Error! Reference source not found.** and **Error! Reference source not found.**. It is the operation with the highest impact due to it being condensed as a single operation. The bolting of the top skin is not comparable as it takes place in two operations due to the requirement for working inside a closed box after the bottom skin has been bolted.

Table 6-10 Identification of process pairs

High Impact, High Commonality
Bolt Bottom Skin vs Bolt Top Skin
Bolt Bottom Skin vs Bottom Skin Rib Drilling
Cleat drilling vs Bolt Bottom Skin
Bottom Skin Rib Drilling vs Bolt Bottom Skin
Front Spar Drilling vs Bolt Bottom Skin

Generally, the processes listed in **Error! Reference source not found.** are processes that should be considered for shared platform approach. However, there is an anomaly in that cleat drilling and bottom skin bolting appear as a pair. Processes that have exact commonality have been excluded from **Error!**

Reference source not found.. These processes already have shared platform systems in place. Rather, this category includes processes that should be considered for a shared platform strategy.

Table 6-11 Identification of process pairs

Low Impact, Low Commonality
Bottom Skin Location vs Front Spar Drilling
Removal of Bottom Skin vs Bottom Skin Location
Locate top Skin vs Rib Location
Front Spar Drilling vs Relocate Top Skin 1 and bolting
Flap Track drilling vs Relocate Top Skin 1 and bolting

The processes that fall in the category demonstrated in **Error! Reference source not found.** should not be considered for shared platform strategy. These are processes that have a large gap metric and are less significant from a cycle time perspective than others. It would be difficult to justify an over investment for these operations.

Table 6-12 Identification of process pairs

Low Impact, High Commonality
Removal of Bottom Skin vs Rib Location
Removal of Bottom Skin vs Flap Track drilling
Removal of Bottom Skin vs Relocate Top Skin 2

Error! Reference source not found. also shows processes that are unlikely to be considered for a short platform strategy. All the processes that lie in this category are typically short cycle time processes.

6.5 Discussion

Shared platform approach is a form of strategic road mapping that promotes a structured design for assembly approach for holistic design and technology product development.

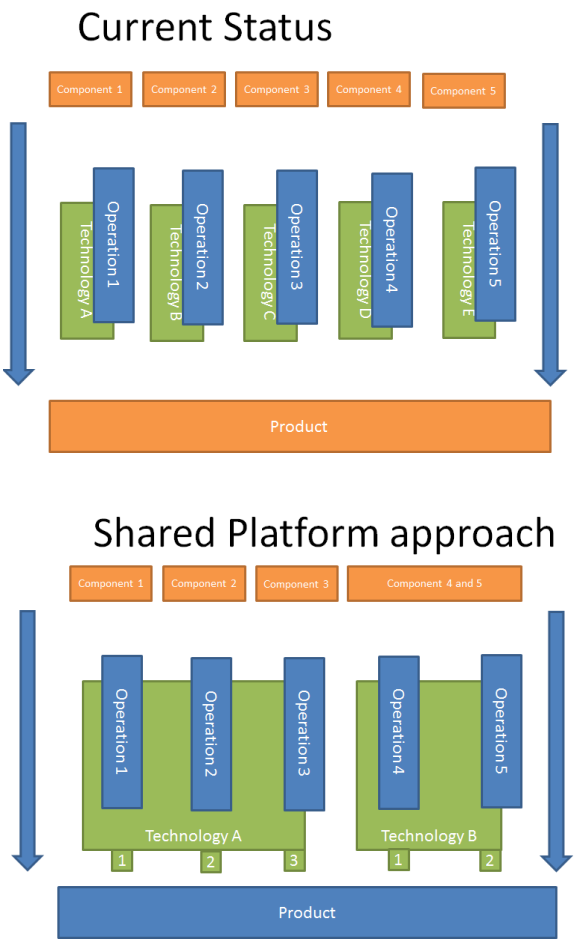


Figure 6-8 Illustrating shared platform approach for Design for Assembly

The adoption of a tool to carry out a macro analysis on all process within an assembly was shown to be useful in identifying areas that can benefit either from design modification for assembly easement or for the identification of areas that can benefit from technology insertion. The tool was also able to demonstrate a link between major operations that could be harmonised as part of a shared platform approach. This was briefly explored and the potential for benefit is substantial.

Implementing such an approach on an existing product, such as the long life legacy commercial aircraft that this analysis was conducted against, is difficult for a number of reasons. The largest obstacle is the risk averse culture within

aerospace manufacturing and the reality that radical new materials and technology are treated with suspicion. However, the innovation in shared platform approach over traditional DFMA methods is the encouragement to look at the product and technology as a single organism.

It is important to note that shared platform approach is specific to a manufacturing environment where movement of the components is undesirable and many manufacturing operations are likely to take place in the same assembly tooling or stations. If the components move frequently in an assembly line for example, this could be prohibitive to the adoption of such an approach as this would require the assembly technology to move with the line.

6.6 Conclusions

The representation of the commonality analysis and the gap metric is not straight forward. Future development should attempt to present these metrics in a way that an engineer is able to quickly form conclusions. In this analysis, there were 361 process pairs. When they are charted on a gap metric graph it is difficult to draw immediate conclusions without deeper understanding. This is important for the industrial impact of such a tool.

Also, a more thorough method to assess impact would be advantageous. In the case study, cycle time was used as a gauge of impact. This is typical of a manufacturing business. However, the complexity analysis from Chapter 4 demonstrated that there are other factors that can alleviate stresses on a manufacturing or assembly system. The operations that were deemed to have low impact were as follows:

- Rib Location
- Bottom Skin Location
- Removal of Bottom Skin

- Top Skin Location
- Flap Track drilling
- Relocate Top Skin 2

Other than the drilling of the Flap tracks, which are deemed low impact due to the limited number of holes in comparison with the other drilling operations, all these operations are to do with location. A critical aspect when carrying out assembly in aerospace applications is the integrity of the assembly. Accurate location is intrinsic to maintaining that structural integrity. It is difficult to capture this in any metric. In Chapter 3, capturing this kind of risk is carried out through feedback on failures. However, that was in redesign scenario. Even in that scenario, if failures do not appear, the risk is minimised and the value of the process is not highlighted despite the possibility of the process being unstable. In a future product development scenario, there are no historically recorded failures to act as feedback and as such the importance of such a process is not captured. Future work should focus on developing a metric to identify risk processes away from cycle time. These risk processes should be targeted for improvement of the long term integrity of the product.

An attempt at validating this method is presented in section 7.4 using a scenario based analysis.

7. VALIDATION APPROACH

7.1 INTRODUCTION

This chapter takes the methods and tools proposed in the previous chapters and attempts to provide some measure of validation. The Chapter attempts to use existing data to do this. Whilst this data is directly relevant to Redesign and Complexity analysis, it is more difficult to validate Shared Platform approach as it is a pure development method. However, it is demonstrated how the method can be advantageous and specific scenarios show that there is great potential in the application of this method.

7.2 REDESIGN FOR ASSEMBLY TOOL VALIDATION

The redesign for Assembly tool presented In Chapter 4 gave an example of how the tool can be applied on butterfly brackets. In this section, the tool is used more extensively. The tool provides real meaning when used in context. This requires data population of a number of other processes to compare against. The tool was used on 6 different processes. These processes were identified for analysis through a combination of recommendations from industrial and programme teams and some analysis of the assembly critical path to identify time consuming areas. The areas processed are as follows:

- Top Skin Front Spar Drilling
- Bottom Skin Panel Loading
- Cleat Installation
- Pylon Machining
- Rib Installation
- Top Skin Panel Reloading

7.2.1 Analysis

Figure 7-1 shows a radar chart comparing the processes against each other. For the purposes of the chart, a normalisation process was carried out to plot the different factors on the same axis.

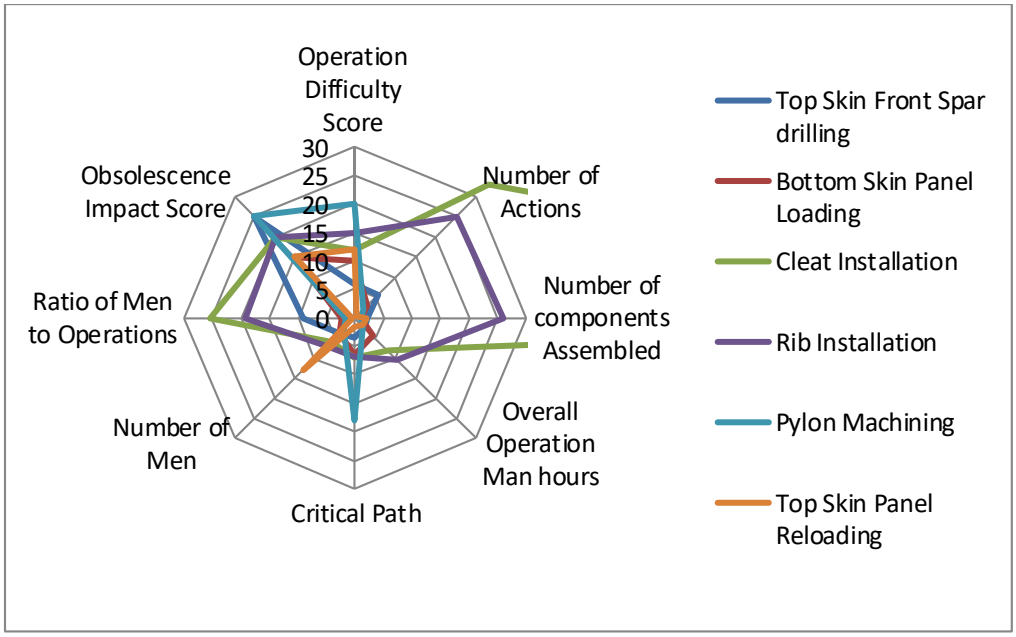


Figure 7-1 showing the analysed processes compared against each other

Cleat installation is displayed in the analysis as a measure of the control. It is shown to score highly in a number of areas compared to the other processes displayed. This is a positive indicator as to the reliability of the tool as cleat installation is a process that has already been chosen for redesign by the business. The indicators explained in Chapter 4 can be split into two categories. The first are typical DFMA indicators and they are as follows:

- Number of components.
- Overall operation man hours.
- Critical path time.
- Ratio of operators to actions.

The second category, are those indicators that relate directly to redesign for assembly of a product already in steady state production. These are as follows:

- Failure score.
- Operation difficulty score.
- Obsolescence Impact score.

Each process displayed in the radar chart shown in Figure 7-1 is thus analysed based on these categories.

Top Skin Front Spar Drilling

This is the drilling process through the top skin and into the front spar. It involves the use of drilling templates and the progressive installation of temporary fasteners. The traditional DFMA indicators appear to illustrate that there is no need for redesign. However, the process is shown to have a high operation difficulty score and a high OBI score. The operation difficulty score is high due to the requirement for specific tooling for back drilling in order to produce datum holes. This stems from the size of the panel components. As to the high OBI score, this is allocated for two separate reasons. The first is that Geometric Dimensioning and Tolerancing methods (GD&T) have evolved in the past few decades and have even been implemented on newer programs. They have not been implemented on this legacy product and thus this datuming issue is present. Also, the datum holes are required to be drilled in large flat areas that have no nearby features that can be datumed from. Thus, operators are required to datum

from the other side of the panel where there are ribs and other features to datum from.

The other contributing factor to the OBI score is that the technology used to carry out this process has been superseded. This process is now fully automated on newer aircraft.

Bottom Skin Panel Loading

This is the initial loading and wrapping of the bottom skin panels on to the ribs. The actual loading of the wing skins was found to be a relatively short process despite requiring highly skilled operators. The time consuming elements were in preparing the skins for loading.

This process was highlighted by stakeholders within the production organisation as an area for improvement. However, the OBI score it received is relatively low. This researcher investigated the disparity between the perceived problems of this process and its reality. The perception by the production teams was that there was a high failure rate due to the forces involved in wrapping the panels around the rest of the assembly and a perception that this induced necessary repositioning of the panel further along the assembly. This researcher carried out a detailed study in this area in an attempt to identify DFA improvements. It was found that the assembly process itself was not problematic and that the process was not found to be obsolete. However, the compliant nature of the component meant that movement during assembly was inevitable. An investigation into better forming processes was also launched. However, even with a more robust forming process, the size and nature of the component meant that this would have limited effect at this assembly stage.

This is a positive result for the tool as the tool indicated that limited improvement could be offered in this area.

Cleat Installation:

This process has been discussed previously in this report. The process is already currently being addressed as it has been identified as a problem area. It is shown here in order to act as a measure of the success of the tool.

Pylon Machining:

The pylon machining being addressed here is the drilling of a support plate in the pylon area. This process is shown to have a high critical path time. This is due to a number of factors related to the components themselves. The material in the pylon area is titanium and as such it is difficult to machine. Also, locating parts around it and using fasteners to secure its location is more challenging due to the material being less compliant then aluminium. At the time that this was designed and launched into production, the processes that were implemented were the most efficient. However, as shown by a high OBI score, there are technologies available now that can offer a more efficient method of assembly. Also advances in GD&T capability have revealed that the tolerance requirement for this area does not need to be as tight as is specified. At pylon machining phase, the tolerance allowance allocated to the components is exceeded by the machining technology. This is due to an increase in the capability of the machining technology over the last few decades. Thus, if the tolerance at machining phase is made tighter, the tolerance at assembly phase can be relaxed achieving the same total tolerance allowance.

The operation difficulty score is also high. This stems from the fact that the uncompliant material is difficult to locate into position and this leads to operators having to adjust the assembly when parts move out of position.
A traditional DFA analysis will have indicated that this area was indeed difficult but that it was necessary and there was no need to change anything. The Redesign indicators inform the engineer that there is potential for improvement.

Rib Installation:

This is the process of assembling the ribs to the front and rear spars. Traditional DFA indicators point to a reassessment of the area as it is a process that lies directly on the critical path and also has a high number of components. However, a traditional DFA assessment would also indicate that the parts are necessary and that they are required to be separate components. The redesign indicators tell a different story. A high operation difficulty score and a high OBI score point towards an opportunity in this process. The high OBI score is due to the same process being upgraded on a newer aircraft program through a modern GD&T analysis. The new process involves a determinant assembly approach and is a more cost effective way of installing the ribs. The introduction of such a process would also reduce the operation difficulty score. This is because one of the main reasons that this was high was because of the difficulty in locating the ribs and adjusting their position.

Top Skin Panel Reloading:

This operation involves relocating the top skin. The top skin is removed from the assembly after it has been drilled in order for cleaning and deburring to take place. It is then relocated on to the structure using the same original method of location. This operation is similar to the process of bottom skin panel loading

discussed previously and shares many of the same challenges. The reason it was also included in this assessment was due to a recommendation by the production teams. The reasoning was that this was a more challenging process then the initial loading onto the wing box assembly as the holes that have been drilled are now required to line up. This is represented by a slightly higher operation difficulty score as readjustment of the assembly was occasionally required. However, as with the bottom skin loading, the operators carrying out this process are highly skilled and are usually able to locate the skin panel efficiently. An over reliance on those operators may perhaps create a bottleneck if they are needed elsewhere but this is offset by the cost of developing a technological solution.

7.2.2 Summary and Recommendations

The tool demonstrated positive initial success. The tool was able to highlight that the cleat installation process was indeed problematic and that it suffered from obsolescence. This corresponded with the business decision to carry out a redesign in that area. Also the tool pointed towards two more areas that could benefit from redesign for assembly projects. These two projects were also highlighted by the factory as potentially profitable. The other areas that were analysed were not deemed profitable and this was the same view of the factory. The one area of discrepancy was the loading of the wing skins. The plant decided to further investigate the form of the wing skins throughout production. However, this proved to be evidence in favour of the methodology and the tool as after the investigation was carried out, no obvious benefit could be identified.

The redesign indicators were able to highlight processes for project consideration where traditional DFA analysis could not. Obsolescence analysis and operation

difficulty assessment were shown to be useful tools for analysis in established production systems.

A deficiency in the tool is that the tool only studies processes in isolation. A process is very likely to be affected by previous processes on the same assemblies or components. This was demonstrated through the investigation into the assembly of panels where a better understanding of the area could only be achieved through a root cause analysis of the component from its machining phase to its assembly phase. Future development of the tool will attempt to factor in component and time related elements

It is important to acknowledge that the tool is specific to this scenario. The methodology, demonstrated in Figure 4-1 is a general methodology that can be applied for any redesign scenario. However, every manufacturing system will require the development of its own tailored tool. Even if this methodology was to be used for another stage of production of the same wing box, the tool would require adaptation to that requirement.

It is typically assumed that critical path is the most prominent factor in making decisions with regards to manufacturing and this is why it is included as a part of this analysis. However, in a redesign setting there are a number of factors that might be prioritised at a particular time. For example, if delivery dates have been established then reducing total operation hours is perhaps more profitable for that product then a reduction in critical path. This tool enables the engineer to decide on which project to pursue based on the current factors that a product is being subjected to.

7.3 COMPLEXITY METHOD VALIDATION

The question to be answered to validate the proposed complexity analysis research is whether the complexity tool gives a real indication of complexity. In Chapter 4, information was gathered from manufacturing stakeholders about key business decisions that were taken with regards to manufacturing improvement. Information on failures in particular areas was also gathered. The processes that went through the complexity analysis are listed in the following table.

Process	Business Decisions/Projects	Failure Information	Relative Complexity Comments (Overall average complexity is 324)
Rib Installation	Design improvement for easier location	High, reports of scrapped ribs	Variable but generally average complexity
Bottom Skin Front Spar Drilling	Automation Proposed	Low	Close to Average. Stable
Bottom Skin Rear Spar Drilling	Automation Proposed	Low	Close to Average Complexity. Stable
Pylon Reinforcement Plate Assembly	As is	High	Constant high complexity. Stable
Top Skin Rib Drilling	Automation proposed	Low	Close to Average Complexity. Stable
Top Skin Front Spar Drilling	Automation proposed	Low	Constant below average. Stable
Top Skin Rear Spar Drilling	Automation proposed	Low	Constant below average. Stable.
Cleat Drilling	Redesign proposed	High	Variable but generally high.
Bolting Bottom Skin	No proposed improvement solutions for legacy optimisation.	Low	Below average. Stable.
Top Skin Bolting	No proposed improvement solutions for legacy optimisation	Low	Ascending, but generally high

Table 7-1 Showing business considerations of the processes analysed under the complexity tool

Three processes have above average complexity. These are Cleat Drilling, Top Skin Bolting and Pylon. In the case of Cleat Drilling and the Pylon area, this also correlates with feedback from the operators of high failure in those areas. It is reasonable to assume that areas with traditionally high failure rates are complex tasks. The complexity metric developed here seems to correlate with this

assumption. This is further emphasised when a shorter process in which high failures is an issue is analysed. This is the process of reloading the bottom skin. The bottom skin is removed for deburring and cleaning after the drilling of the ribs, front spar and rear spar. It is then reloaded onto the structure, locating onto the pylon monocle, gear rib and the pylon area. The complexity calculation yields an indicator of 417. Considering that average complexity is 324, this is significantly above average thus validating the conclusion that a high complexity indication corresponds to a high failure rate. This is particularly useful for development projects that do not have historical failure data.

6 processes have stable complexity. These include the various aspects of bottom skin drilling, pylon installation, top skin drilling and the bolting of the bottom skin. Other than pylon installation, all those processes with a stable complexity also have a low failure rate. This is again a positive indicator for the validity of the tool. Further, processes with a stable complexity, other than pylon installation and bottom skin bolting have been automated in other programmes and companies and are intended to be automated here as well. This lends further credence to the validity of the complexity metric as typically only simple, repeatable processes are automated (Kalpakjian, 2001). As for Pylon installation, its complexity has been discussed previously. It is a process that has a stable complexity because of its relatively short cycle time. Bottom Skin bolting presents a different challenge. The process is a consistent process in its level of complexity and analysis of the process reveals that it is indeed, highly repeatable. The reason that it is not considered for automation is due to the nature of the assembly. Automating a solution is not beyond the realms of possibility, as demonstrated by Sherick (2015). The challenge is not in the assembly components themselves; rather it is

in the production system as a whole. In this example, the production system was commissioned in a time when the possibility of automated fastening was still far off. This issue is addressed in Chapter 6.

The idea of low complexity consistent activities is further explored in another shorter process. This is the initial panel load of the Top and Bottom skins. Their complexity values are shown in Table 7-2. They are both relatively short processes, and the feasibility of their automation is unlikely to be positive. However, this analysis isn't looking at feasibility but at the relationship between complexity and automation.

Process	Complexity Value
Top Skin Loading	345
Bottom Skin Panel Loading	317
Rear Spar Loading	522

Table 7-2 Complexity values for Skin Loading and Rear Spar Loading

Both operations have complexity values around the average mark. They are both similar operations with Top Skin loading being slightly more complex due to the components located onto the structure as separate entities and not as a subassembly as is the case with the bottom skin. The process of loading the panels has been automated in other applications. There are examples of such systems in the aerospace industry demonstrated in Figure 7-2. However, as mentioned, the feasibility of introducing such a system on an existing product line is not favourable. Usually such technology is introduced on new products.



Figure 7-2 Showing an example of panel loading technology

On the opposite scale, Table 7-2 also shows the complexity value for the loading of the rear spar. This is very high owing to the number of critical interfaces that are associated with the rear spar and the leading edge. Currently, this researcher has not come across any cost effective automation system that is able to provide a solution for the installation of the rear spar. Locating these components is very critical to the integrity of the assembly and a system has not been developed that manufacturing engineers will feel confident in relying on.

Having looked at these examples it appears that the proposed theory that there is a relationship between complexity and automation stands firm.

7.3.1 Conclusions

The proposed complexity tool set is shown to be beneficial for both backward applications such as legacy production system analysis and development applications. In the case of legacy applications, it can be used to identify areas of

potential improvement. The toolset is validated through observing recent business decisions and projects and comparing against complexity indicators.

Development applications of the tool set are perhaps more useful. It is proposed that the tool set is used during the planning stage of developing activities similar to cost planning and cycle time exercises. The benefits of this are further explored in Chapter 6.

The tool proposed in Chapter 4 provided more detailed analysis but relied on existing data to offer positive results. The main difference between the method and tool discussed in this Chapter is the lack of this requirement. Other differences are that the Complexity analysis method takes a view from a higher level, disencumbering itself from some of the specific details of the Redesign method. Further, in some areas, the Redesign method requires input from operators. Human input, although necessary in this case is always subjective and can suffer from bias. The Complexity analysis relies on analytical data. This is positive because of the lack of subjectivity but also negative in the lack of input of valuable tacit knowledge. A simple example of the difference can be seen when considering positional accuracy requirements during assembly. Whilst in the complexity analysis the positional accuracy that would be taken into consideration would be designed and planned, the Redesign method would bring forth the reality of whether that positional accuracy can be achieved consistently in steady state production.

7.4 SHARED PLATFORM APPROACH VALIDATION

Validating the proposed Shared Platform Approach method is difficult due to the timescales involved in applying it to a development program. However, its potential can be shown through a scenario analysis. Two scenarios are discussed to demonstrate this method. The first scenario involves two processes that share a large percentage of motion characteristics. This is the Pylon Drilling process and general skin to structural drilling. The second scenario takes two seemingly differing processes, drilling and bolting and demonstrated the benefit in considering them under a shared platform approach.

7.4.1 Pylon drilling vs Structural drilling

The two processes are compared in Table 7-3. The first step of the proposed method is to define process vectors. This has been carried out and demonstrated in section 6.3.1. Each step after this step is discussed individually:

Identify Processes with high percentage of common Characteristics:

	Pylon Drilling	Structural Skin Drilling
Direction of Motion	Z	Z
Positional Accuracy Required (mm)	0.2	0.2
Force Requirement (N)	300	100
Payload Capacity (kg)	5	12

Table 7-3 Comparing motion characteristics of pylon drilling and skin drilling

There is commonality in motion axis Z and also that both take place in the same motion direction. There is also commonality in the required positional accuracy. The differences are in the forces involved in carrying out the drilling operations and also in the weight of any potential robotic end effector.

Benchmark review of optimal processes and technology

Aerospace structural drilling, of which skin drilling is a part of, has been automated in numerous applications (Hempstead et al., 2006, Atkinson et al., 2007, Devlieg, 2011, Gray et al., 2013, Adams, 2014). As discussed in Chapter 4, the complexity of the process and its cyclic nature incline it towards automation. Based on the widespread application of automated structural drilling, this concept is mature and would be placed at TRL9; this means that not only is the technology mature but it has been implemented in the past effectively.

As for the drilling of the Pylon area, progress has been slower in the development of technology solutions to optimise this process. Historically, positive feed Rack fed drills, shown in Figure 7-3, have been the most practical solution. These units are typically heavier then structural drilling units due to the higher forces required to cut through titanium and also due to the larger hole sizes and stack thicknesses required in this area. This is all reflected in this process having a high complexity, demonstrated in Chapter 4.



Figure 7-3 Example of a Rack Feed drill. (Dessoutter, 2017)

Due to the complexity of the process, attempts at automating titanium drilling have not been as numerous as structural drilling. Hogan et al. (2003) demonstrate an industrialised system for Titanium drilling using a Cartesian positioning system for the end effector. Also, Bi and Liang (2011) explored the idea of automating this process and developed an end effector carried by a robot arm. The results produced were positive. However, whereas an industrialised and implemented system such as the one implemented by Hogan et al. (2003) would be considered at TRL9 maturity, the work carried out on the robot arm would be considered at TRL3 maturity. There are flexibility advantages in using a robot arm over a Cartesian system but this does not affect the shared platform strategy. Both technologies are platforms that are also consistent with structural drilling and thus there is scope for a shared platform approach for these two processes.

Over investment justification:

The gap between these two operations is demonstrated below in Table 7-4. For the purpose of this demonstration, it is assumed that a robot arm is the preferred choice.

		Front Spar Drilling	Pylon Drilling
Raw Data	Average Complexity	283	412
	Technology Maturity	9	3
	Positional Accuracy Required (mm)	0.2	0.2
	Force Requirement (N)	100	300
	Payload Requirement	5	10
Alignment Factor	Complexity	2.766666667	7.066666667
	Technology Maturity	9	3
	Positional Accuracy Required (mm)	2	2
	Force Requirement (N)	1	3
	Payload Requirement	1	1
	Total	15.76666667	16.06666667
		Gap	0.3

Table 7-4 demonstrating the calculation of the gap metric between Structural Drilling and Pylon Drilling assuming the adoption of a robot arm.

The gap metric is relatively small, indicating that the over investment required is minimal. The average gap for all processes when compared against each other is 23.26. The only reason that there is any gap at all is the requirement for the platform to absorb and exert greater forces during drilling. As structural drilling is a process that has already been automated previously and evidence of that benefit can be demonstrated, then it is likely that in any new development program that requires a similar operation, an automated solution will be sought. If that automated solution is using a robot, then the gap metric indicates that a minimal investment can potentially mitigate the cost of another future investment in addressing the pylon drilling operation through a similar automated technology. Further, the knowledge that the pylon drilling area is a time consuming and complex task enforces the opinion that this is strong evidence that the over investment at this stage is valid.

Shared Platform Strategy

The proposed strategy for this scenario would be to invest in a robot arm or a Cartesian system that could be a platform for both structural drilling and pylon drilling. Further the development for robotic drilling of pylon should be road mapped and resource and budget should be allocated over the coming years to address this development. A targeted insertion date should also be identified.

7.4.2 Structural Drilling vs Structural Bolting

As with the previous pair of processes, these processes are part of the wing box assembly production system and thus share the same motion characteristics as before.

Identification of Processes with common characteristics:

A motion characteristics analysis of these two processes indicates that they are highly compatible as demonstrated in Table 7-5 Comparison of. The differences between force application requirement and payload requirement are minimal and are likely to fall within the ability of the robot.

Motion Characteristic	Structural Drilling	Bottom Skin Bolting
Direction of Motion	Z	Z
Positional Accuracy Required (mm)	0.2	0.2
Force Application Requirement (N)	100	50
Payload (Kg)	5	3

Table 7-5 Comparison of bolting and drilling operations.

Benchmark review of optimal processes and technology

At this stage, it becomes clearer that these two processes have a major difference. Although both processes operate in the same Direction of Motion, bolting is a process that requires access to both sides of the work piece. This is to insert the bolt and then attach the nut on the opposing side and apply a torque to complete the fastening. Drilling operations only require access from one side of the work piece.

The technology and automation that has been developed for structural drilling have already been mentioned. As for bolting, automated bolting applications for aerospace assembly have been implemented extensively in the past (Holden, 2007, Truess et al., 2003). This has traditionally used a high accuracy Cartesian

monument machine on components that have limited restrictive features, such as flat panels being assembled together with structural stiffeners. More recently, collaborative robots have been deployed as shown in Figure 7-4 but are not yet widespread. The more flexible robot arms would be more advantageous to a shared platform approach between this pair. Therefore, it can be concluded that as before, structural drilling is at an advanced technology maturity (TRL9) and automated bolting, although a fully developed and implemented technology is at TRL6 due to its infancy in widespread adoption.



Figure 7-4 Showing a bolting system that uses robot arms, positioned either side of the work piece (Assemblymag, 2015)

Over investment justification:

Interestingly the average gap between these two kinds of processes is 5.2. When compared against the average gap across the manufacturing system, 23, this is low. This is because, on a pure physical motion and force characterisation, these two processes are similar. If these processes were compared from a current technology and component analysis, they would be deemed to be very different. The objective physical and motion analysis allows the engineer to view them in a

different light. On the basis of the gap analysis, some justification can be made for considering these two processes for shared platform approach.

Shared Platform Strategy Definition

The key to a shared platform approach is design with an intent to erase prohibitive differences. In the case being presented here there are many development routes that can be explored, but within the context of redesign for assembly the options for redesign are more limited. The intention is to present the challenges that need to be overcome to achieve a shared platform approach and then a demonstration of some of the capital cost savings that can be gained.

In newer assembly lines, attempts at automating drilling operations have been successfully implemented using robots or monument automation platforms. Monument automation platforms are large structures that are built around the work piece to carry out specific automated tasks. Generally speaking, industrial automation is targeted at highly repeatable tasks (Olsson et al., 2010). An example from the automotive industry is spot welding.

At first glance, the operations of drilling a series of holes and bolting those same holes appear to be highly repeatable. After all, as demonstrated in the various analyses of those operations above, the operations are largely cyclic. However, there are two aspects that are unique to large volume aerospace assembly that make the introduction of industrial automation challenging. The first is the higher level of positional accuracy required. (Olsson et al., 2010). Robots are typically able to be highly repeatable but cannot usually achieve that repeatability with the required aerospace level of accuracy. This is one of the reasons that monument automation has sometimes been chosen instead of robot automation despite the cost being significantly higher. The second aspect is the variability in aerospace

structures. Aerospace structures are large relatively thin structures and are thus compliant. This means when a reasonable force is applied, either through the operation taking place or through clamping, there is a strong possibility that they will move. Thus, any automation system is also required to locate and manage on a variable assembly. The extent of the variability will be different on every assembly. (Holt and Clauss, 2015)(Tomchick et al., 2015).

Thus shared platform approach attempts to limit the number of automation operations required. The starting point is to attempt to make the two seemingly different operations able to be performed in the same domain. The main difference is that one operation is a material removal operation and one is a torque application operation. However, the aim is not to make bolting and drilling the same operation, but to limit the differences. **Error! Reference source not found.** shows an example of how drilling and bolting can be categorised into areas where some of the characteristics are similar.

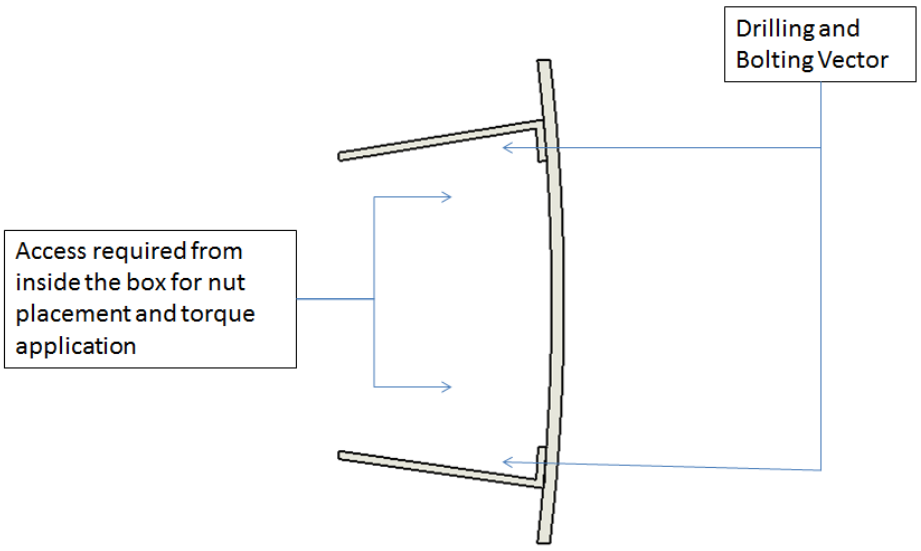


Figure 7-5 Example of a spar and skin section

There are two main differences in these two operations. The first is seemingly unsurmountable. The same end effector will not be able to drill and bolt. The second difference is in the requirement of bolting to have access from both sides of the work piece. A fastener that can be installed from one direction would negate the need for access to both sides of the work piece. This technology exists, currently referred to as blind fasteners (Alcoa, 2016), however the technology exists for a particular application and extensive development and testing would be a requirement before major commercial aircraft manufacturers would be prepared to accept it. Alternatively, a design solution can be implemented where both operations are replaced by a single operation, for example; adhesive bonding (Higgins, 2000). Any of these alternatives would require significant investment of money and would also require time for development however the harmonisation of operations will inevitably lead to reduced assembly cost and over the course of a long life product such as an aircraft, would likely lead to a significant saving.

The reality is that the impact of these two processes is such that a justification could probably be made for separate investments for each one.

8. CONCLUSIONS

8.1 CONTRIBUTIONS TO KNOWLEDGE

The Redesign Method presented in Chapter 4 demonstrated two main contributions to knowledge. These are the record and use of two novel factors when considering where to carry out redesign or optimisation projects in an assembly system. These factors were:

- Obsolescence Impact
- Operation Difficulty

Traditionally obsolescence has only been considered with regards to when parts or suppliers are no longer available. In this research obsolescence is presented in practical light for continuing assembly optimisation. This was that obsolescence is when a process or technology is no longer competitively viable. Also presented was an assessment method to determine levels of obsolescence.

The second major knowledge contribution in this Chapter was the assessment of operation difficulty. This research presents a generic method to developing an operation difficulty assessment; to identify the key factors in an assembly process that add complications and then to sum the number of added complications together. This was demonstrated for the assembly of aircraft wings and was shown to be a successful metric.

The main knowledge contributions in Chapter 5 is an overview assessment of a manufacturing or assembly system using specific indicators for that

manufacturing or assembly system that equate to complexity. In this way the engineer is able to plan manufacturing easement either through design or technology development. Although complexity analysis exists in many forms it has not been implemented before as an overview on a full assembly system. The demonstration of the case study showed that this was a positive method and that the indications drawn from the patterns were mostly valid.

The contribution to knowledge from Chapter 6 is the use of vector trajectory for process classification and the adoption of assembly technology development planning in the DFA process. This is particularly useful for long life products that are typically redesigned.

8.2 SUMMARY

Chapter 1 outlined the aims and objectives of this research. It was identified at an early stage that the existing methods and tools that were generally accepted for DFA were not wholly applicable for the Aerospace assembly domain.

This research developed three techniques to support DFA in this domain. The first method acknowledged that New Product Introduction was uncommon in commercial aircraft development with the industry only demonstrating an appetite for redesign to achieve performance improvement. Thus the opportunities for major design for assembly changes on existing product architecture are limited. The method developed a way to carry out an analysis of an existing product and its associated assembly processes that could provide insightful information to an engineer when making decisions on component or process optimisation projects. This allows an organisation to prioritise projects using existing empirical data thus

saving decision making time and also limits the pursuit of projects that are unlikely to lead to desired outcomes.

The second technique acknowledged that the redesign method was not suitable for new product introduction analysis. Thus a method for a holistic analysis of the product architecture without the detailed tacit knowledge that was available in the redesign method was developed to carry out a complexity analysis that could provide insight into where the manufacturing system is likely to experience problems or bottle necks. This is beneficial as it enables a macro view of a production system which can allow an engineer need to monitor the impact of processes on the wider production system. It also allows the engineer to identify patterns in that macro view that maybe indicative of areas that are favourable for technology introduction such as automation.

The final method, Shared Platform Approach, acknowledged that manufacturing and assembly technology development effort in the aerospace industry is costly due to the typically bespoke requirement. This method allowed an approach to product development that acknowledged future assembly technology development. This method will enable an organisation to carry an element of cost mitigation for future technology insertion by designing products that can share technology platforms.

The research presented in this Thesis has successfully achieved the objectives stated. The methods presented and validated are beneficial tools for the progression of the DFA domain.

8.3 FURTHER WORK

There are a number of areas that this research was not able to explore that would expand the work.

The development of a specific cost estimation tool that can calculate specific development cost.

This relates specifically to Shared Platform approach. This research proposed the use of existing cost estimation tools to feed into a shared platform analysis. To further enhance the shared platform analysis a specific cost estimation tool would be beneficial. The tool could potentially take into account specific trends in development of those specific technologies that are likely to be utilised in aerospace assembly. For example, trends in robot development could be analysed. Robot accuracy development throughout the previous development cycles and the likely costs involved and estimated future prices could be calculated.

Development of automated assembly simulation during design.

Another aspect of this work that this researcher feels could also be beneficial is the implementation of automated assembly simulations during design. This research has identified a number of key factors that influence complexity or can contribute to a shared platform approach. If during the design phase, assembly interface requirements can be identified, an automated tool that can generate assembly simulations with associated manufacturing costs would be highly beneficial during development.

For example, build philosophies are now typically developed alongside product design. If software is developed that contained the factors discussed in this research and the associated cost estimation developments, then upon inputting build philosophy data, the software will generate initial estimated development costs as well as technology suggestions.

The adoption of the redesign method as part of PLM

Product Lifecycle management (PLM) tools are now standard during product development. However, whilst PLM recognises relief through redesign it doesn't facilitate it. This researcher believes there is an opportunity to realise redesign for assembly or redesign for X as part of PLM strategy. This is especially true for PLM for aircraft where redesign is expected and redesign for assembly should be a prudent course of action considering the long life of the product and the developments of manufacturing and assembly technology throughout that life.

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