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DESIGN FOR MANUFACTURE:
A METHODOLOGY TO EVALUATE AN AIRCRAFT DESIGN IN ORDER TO ENSURE ITS MANUFACTURABILITY.

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A THESIS SUBMITTED TO THE UNIVERSITY OF
HUDDERSFIELD IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY

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Abstract

The aim of the research is to develop a methodological analysis of problems in the area of design for manufacture in low volume high complex products found in the writer's workplace. The majority of research in this area has been around high volume products, such as automotive products and little consideration has been given to designing complex products from industries like aircraft manufacture.

This research evaluates design for manufacture (DFM) information in the design life-cycle (DLC). The author's research introduces a unique DLC process, one which structures decisions and data transfer through the DLC. The research also looks at current academic work and introduces industrial issues present in today's environment.

It is crucial to the design of a product to select the appropriate design environment in which it operates, as it will structure the way the engineering activities are established and developed. It is also important for the organisation to decide on the environment in which the design definition should evolve. Therefore the research reviews the different design definition environments, these were carefully analysed by the author.

The evaluation of a design to ensure its manufacturability is a major element in the research, a review of previous work has highlighted that within current publications there has been little work in this area. The research has developed a methodology to evaluate the robustness of a design. It not only looks at the engineering design but also evaluates its adherence to customer requirements and the effect on cost for the overall product life-cycle. It also considers industrial needs for a reduction in the length of design life-cycle, while ensuring a reduction in manufacturing costs. There are two main contributors to this, firstly the use of key characteristics and secondly, the ability to control the manufacturability of a design. The author has developed a novel software tool enabling efficient evaluation of a design.

The author discusses his contribution to existing knowledge in three main areas of the research. The most significant being the introduction of a tool to evaluate a design early in the design life-cycle to ensure manufacturability. To validate the research the author introduces the reader to three experimental phases. He validates his methodology by analysing the design of various aircraft assemblies discussing his findings of how manufacturable the designs are. This leads to the conclusion that the author's research adds substantial knowledge to the area of design for manufacture.

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Acknowledgements

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Chapter 1 Introduction

1.1 Introduction and Purpose

In many cases an organisation's prime objectives are to provide products or services cost effectively to a customer regardless to whether the organisation is profit making, a charity or a governmental department. It is therefore crucial that the organisation is geared to these prime objectives. Anything that occurs within the organisation that does not contribute directly or indirectly to the customer requirements should be placed under scrutiny. Along with addressing the customer requirements, if the organisation is commercial it will have to make a profit for its shareholders.

When designing a product the design team should go through a number of specific steps to allow the design of the product to develop. This helps control the whole process and gives direction in the decision making process. These steps are sometimes referred to as the design life-cycle (DLC).

Designing a product in this way seems to be an effective way to control the product through the design. However when designing large complex products like aircraft, there are many thousands of components to design that have to be assembled in many hundreds of sub-assemblies (Weber 1994). Along with the amount of individual components to design, there is the additional complexity in the number of engineering disciplines and information involved throughout the design process.

There are many functional disciplines contributing to the decision process in the aerospace industry including: design engineering; aerodynamics, stress and fatigue analysis engineering; thermal analysis engineering; electrical engineering; systems engineering; weight engineering; manufacturing engineering; tooling engineering; estimating; business management etc. This information has to be collated and analysed through the design process to deliver a product that meets the customer requirements at an acceptable cost. Although there is extensive research around the design process, there are few papers that directly look at a structured interaction of design and manufacture in the production of complex products.

This thesis looks at the current DLC models that have been and are currently used within product design and extends the approach.

If the organisation is going to make the profit predicted or deliver the design and product on time, the whole DLC period may have to be compressed while dealing with this mass of complex information. For this to be achieved this research focuses on the overall design definition / customer requirements through the design process.

Once the design has been delivered and the manufacture of the products begins, designers may well move on to the next product without an understanding how their design has effected the overall organisation and the profit margins required for the share holders, leaving the manufacturing environment to deliver the product to the customer requirements, cost, delivery, quality etc. Current research indicates that although design costs consume approximately 10% of the budget, typically 80 % of the manufacturing cost is determined by the design of the product (O'Driscoll, 2001). Therefore, no matter how creative manufacturing engineers and production managers are, they cannot influence the manufacturing cost of a product by more than 20%.

With this in mind the research introduces a novel design evaluation technique which can evaluate the design in the early stages of the DLC and predicts the effect in manufacturing, enabling focus on customer requirements while considering the effects on the DLC span.

This outlines the scale of the information flow and the decisions that need to occur in the DLC and, in addition, as the design matures there are major factors such as Design for Manufacture (DFM) that need to be introduced to ensure the long term survival of the organisation (Boothroyd 2001).

1.2 Aircraft Industry Design

The aircraft industry, in terms of manufacturing, is classed as the production of low volume high complexity products when compared to other industrial sectors such as the automotive industry. This environment requires many challenging and complex decisions to be made when designing a product to meet customer requirements. These need to be understood and discussed in detail in order to develop a design evaluation tool that will assist in this low volume high complexity arena.

Customers spend many billions of pounds a year on aircraft, both military and civil. The span time for the design process for aircraft from receipt of the initial customer requirements, to when the product goes into service can take decades. Globalsecurity.org (no date) discusses the life-cycle of the F22 military aircraft where in October 1986, the F-22's Key Performance Parameters were established and in August 1991 the Engineering and Manufacturing Development phase started. These phases led to the F-22's first flight in September 1997 and went into operational service in 2005. This is due to the many steps and disciplines that are involved and the fact that an aircraft has to comply with a huge regulatory framework ranging from manufacturability, structural compliance through to qualification and airworthiness. Hence if the design incurs issues in the design life-cycle which are not acted upon it is very difficult and very expensive to go back and rectify them. Therefore incorrect decisions made in this process quickly manifest themselves into a collection of errors that may be carried, potentially, for the life of the product due to the complexity of the design process and final certification for flight. One of the best ways to illustrate this is by an example from a typical design decision that occurs in the aircraft industry. What may seem a relatively straightforward decision in the automotive industry can have a complex network of dependencies within the aircraft design life-cycle. An example would be the selection of fasteners for a specific area where comparisons would have to be made for location, type, size, quantity etc. Firstly, the fastener load allowable needs to be known, this is the load the fastener can withstand before destruction occurs and involves the fastener suppliers. The load in the area where the fasteners are required needs to be derived. However, to determine the loads in a specific area will require information from the aerodynamic loads, these maybe derived from past experience, wind tunnel testing and prediction using computational fluid dynamics software. This data will feed into the aircraft finite element model (FEM). Further detailed FEM's maybe required to establish the load in the specific area for the fasteners. This process is iterative. As the design of the product changes the FEM model will be updated and hence different requirements may emerge for the fastener requirements. The above example is a very much simplified process, in practice there are many other factors to be taken into consideration, but for this example it highlights how complex the process is for the selection of even a simple fastener due to the weight constraints of aircraft their margins of safety are less. In other industries the safety margins can be much higher hence making this less critical than that of the aircraft industry.

Once the fastener size and quantity have been defined other disciplines in the organisation may have requirements. Assembly manufacturing engineers may have problems with accessibility to install the fastener. Therefore the pitching of the fasteners may vary. This will lead to the re-calculation of the loads to ensure the requirements can be met. The mass engineer needs to calculate the mass requirements and may request fewer fasteners or more fasteners to reduce the weight in the structure and skins. Each time a requirement is specified the load may have to be re-calculated until the desired design intent has been found. Management of this data is also crucial as there are millions of fasteners in an aircraft structure.

A future example where the aircraft industry has additional complexity over many other design industries is the mass of an airframe; this would be a crucial requirement from the customer. Weber (1994), states that aircraft are weight critical; every pound of unnecessary aircraft structure weight reduces aircraft performance, aircraft payload, or the distance the aircraft can fly without refuelling. Every pound of aircraft weight requires fuel to fly it for the life-cycle of the aircraft. Fighter aircraft structures are designed for a life of 6,000 + flying hours. This translates into a fuel cost of approximately $50,000 per pound of aircraft weight over the life of the aircraft.

The examples discussed highlight some of the added complexities that the design process has to consider during its maturity. This research aims to aid with this decisions making process to help achieve the product to customer requirements, at the correct quality and cost to the organisation.

1.3 Aircraft Manufacturing Issues

Manufacturing has similar issues to that of the design. Just the sheer quantity of parts when manufacturing an aircraft will create issues over those in, say, the automotive industry. Since many more components and processes are used, the potential for producing more defects within manufacturing is much higher. One of the main areas that benefits manufacturing is the ability to design out the manufacturing defects by changing the design; this is commonly referred to as design for manufacture (DFM). The aim of this is to design potential manufacturing errors out to achieve a product that will be manufactured within cost and quality ensuring that the product meets the market place in the required time frame. As stated earlier, 80 % of all defects are designed in during the design life-cycle.

The DFM concepts have been stretched out to design for the environment, for disposal etc. The many different areas of DFM have been collated into ”design for X” concepts (Kuo 2001). However manufacturing engineering generally do not get their own way in the design feature of a product due to the many different requirements in complex products design, as discussed in the previous section

1.4 Research Questions Aims and Objectives

The aim of the research is to develop a methodological analysis of the problems in the area of the design and manufacture of low volume high complex products found in the writer’s workplace. The literature review revealed a lack of research in this important area. Whilst recognising the impact of design upon manufacture, DFM researchers generally fail to highlight and justify the critical importance that the manufacture of complex products, such as airframe, has on the design process. The majority of research in this area is around high volume products, such as automotive products and little consideration as been given to designing complex products from industries like aircraft manufacture. These findings make it necessary to answer a number of questions which need to be addressed by the research. The following questions were defined in order to provide direction to the methodology and work plan of the research process:

1. What tools and methods are currently available for design and manufacture of low volume, high complexity products and how effective are they?

   By answering this research question, it is intended to gain understanding of what the present tools and methods for design and manufacture of low volume high complexity products are, how they are used for the purposes of achieving the customer requirements and how effective they are.

2. What are the current approaches to managing the design life-cycle as outlined in papers from current academic research and what pros and cons do these life-cycles have in a low volume high complexity environment?

   This question will address the theoretical approach used when designing these types of products and how well this addresses and accommodates highly complexity products. Once the pros and cons have been defined, a new design life-cycle can be developed to aid the design of complex products such as airframe manufacture.

3. In what type of Design environment should the DLC operate?

   Addressing this question will involve studying the current design environment that has been established in academic literature, looking at each environment individually and comparing these with each other to ascertain the optimum design environment that the DLC for aircraft should operate in.

4. How can design for manufacturing effectiveness be measured in the design process?

   By researching the current academic work in DFM and the effect this has on the design. This will enable the research to establish benefits of DFM and how it affects the design.

5. Can a tool be developed to predict what effect DFM techniques have on the finished design, in terms of cost and quality?

   Addressing this question will produce a novel design tool that can be introduced into the DLC. It would help produce a more robust design and potentially reduce the time frame from the initial stages of the product to the final manufacturing and sales of the product.

It is appreciated that simple answers to the above questions do not exist. Therefore, the research needs to focus on a number of related research areas and come up with a comprehensive report on each of them to answer these key research questions. The research will look to achieve the following objectives:

1. To review the literature to establish current general approaches to product design.

2. To review current approaches in the design life-cycle and design for manufacture in the design of low volume, highly complex products. Review techniques that

enable design for manufacture to be deployed into the design life-cycle will also be examined.

3. To develop a novel improved design life-cycle model that caters for the design of low volume and high complexity products that emphasizes adherence to customer requirements, controlling the design inputs to achieve the desired outputs.

4. To categorise the current design environments that the design life-cycle operates in, analysing their strengths and weaknesses and identifying which environment would benefit a low volume high complexity product during its design.

5. To produce a novel design for manufacture tool that can be used in the author's novel design life-cycle to access how decisions made during the design stage will affect the overall cost and quality of the product when in manufacture.

1.5 Research Methodology

After defining the objectives of a research project, it is essential to decide which research methodologies to use for their achievement. Each method of conducting research has its strengths and weaknesses; therefore it is important that the correct research methodology is selected to achieve the desired results. To successfully achieve the research objectives, which were listed in the previous section, the researcher decided to employ a research methodology which consisted of a literature review to establish other work in the topic area, a theoretical experimental phase which applied the research tool and demonstrated feasibility, followed by industrial case studies in which the performance of the tool was validated.

The intention of the methodology selection is that the initial model will be verified by a theoretical experimental phase. This will help demonstrate the robustness of the tool before embarking into an industrial experimental phase which will be time consuming.

The research method will be used in the process of fulfilling the following briefly defined tasks. Chapter 3 provides more detailed view of the research methodology:

1. Conduct a literature review in the area of design for manufacture, design life-cycle, design environments and structured approaches to design.

2. Expert interviews with industrial specialists will be undertaken to review issues that are present in the industrial sector. A comparison will be made between current academic research and the industrial issues identified. The author will use a combination of these to develop a proposed novel solution.

3. Undertake a theoretical experimental phase of the design evaluation tool; this will validate the ability of the tool to meet the established requirements, along with the validation of the mathematics employed.

4. Undertake a series of Industrial case studies. The products have to be selected carefully ensuring they are complex enough to highlight the methodology around the design evaluation tool. A fully comprehensive statistical process control environment should be in evidence to provide the design evaluation tool with robust manufacturing data.

5. Validation of the design evaluation tool via an experimental phase. The data output from the design evaluation tool will be compared with the costs, defects etc. arising from the actual manufacturing data. From this a comparison will be made between the design evaluation tool and actual industry findings.

1.6 Overview of the Thesis

This first chapter introduces the reader to the area covered by the research. It presents the research questions, aims and objectives, and the methodology which has been used to achieve them. The chapter also introduces the reader to the structure of the thesis.

The second chapter reviews the literature on the design life-cycle, the design environment, DFM techniques and structured approaches to design. It looks at the tools and methods used in these areas to ensure the final product from the design meets both the customer and company's objectives. Most importantly it establishes the novelty of the work to ensure that it provides a genuine contribution to knowledge.

Chapter Three discusses how the research methodology will be used for the achievement of the research objectives that were established. This chapter gives an account of the experimental phases that have been defined, along with the process of the validation of the design evaluation tool and discusses the potential refinements to the research that the experimental phases will deliver. This chapter will also discuss how the methodology is going to help achieve the research objectives.

Chapter Four describes the weaknesses in the current academic work that help produce the objectives listed in chapter 1. This chapter discusses the current academic research in chapter 2 and identifies the areas in which the current research does not offer solutions to the issues that are encountered in today's high complex low volume environment. It will look in the main areas for the design life-cycle, design for manufacture and how their data can be used to help drive the business needs.

Chapter Five discusses the selection of the solution to the problems discussed in chapter four. It introduces a novel design life-cycle that manages the critical information flow in high complexity product design. Once this stable design flow has been established it develops a design evaluation tool which mathematically analyses the design and measures the potential output to the manufacturing environment. This enables changes to the design to be strictly controlled to establish a robust design. This will also enable the business to manage potential problems that may occur in manufacturing prior to the occurrence of these.

The industrial experimental phases undertaken to validate the design evaluation tool within the research are described in chapter six. There are a number of experimental phases discussed in this chapter starting with a theoretical experimental phase which looks at what outputs have been achieved from the set input criteria. Further experimental phase projects carried out in a collaborating company are discussed. The chapter discusses how the design evaluation tool has been validated and how the outcome for these has been introduced back into the design evaluation tool, continuously improving the data. The benefits for the companies are also discussed.

The concluding Chapter summarises the findings of the research and its significance for the design and manufacture of low volume high complex products. The outcomes of this chapter form a part of the suggestions for further development and research in the area of design evaluation and how the research philosophy can be further developed to become a integrated part of today’s and future design theories.

Chapter 2 Literature Search

2.1 Introduction

This chapter discusses the literature covering the design life-cycle and the importance of the environment in which this operates and how this relates to the level of detail in the design for manufacture of the product. Careful considerations of the definitions of the design life-cycle and concepts of design for manufacture follow and introduce the reader to the opinions of experts leading to the formation of a definition of the detail design process which will be sustained throughout this thesis.

The chapter proceeds with a more detailed discussion of the essentials of today's design life-cycle and, in particular, how the role of design for manufacture interacts with the design of a product, including the cost benefits for organisations as a whole when designing such high complexity products as aircraft.

A major part of the chapter will be dedicated to design for manufacture concepts and some of the tools and methods used in this field. It will describe the current state of this area and how it interacts with the design of the product

2.2 Design Life-cycle

2.2.1 Introduction

When designing a product there are certain natural processes that have to occur to achieve the end product. Firstly one needs to know what the product is going to be used for; i.e. who will be the customer and what market it is intended for? How will the designer ensure that the product is fit for the purpose of the user? Will it be strong enough? Ensuring this will involve the selection of materials and the design of certain features to ensure its strength. In addition to this, the manufacturer needs to be able to manufacture a product at the desired cost and it needs to enter the market place at the correct time.

This is a very simplified view of the thought path that may occur when designing any product. However, when designing a product with any complexity it would not be sufficient to merely use the simple steps above. To ensure the design is structured efficiently and correctly it has to follow a design life-cycle. This is a very structured way of designing a product to ensure that the designs are in the correct order. McCue (1994) lists a number of basic objectives that the life-cycle should achieve and following this structured life-cycle will enable an organisation to:

1. Ensure full information is available and accessible for the design.
2. Identify and eliminate unnecessary work.
3. Identify and improve the use of all resources.
4. Improve planning and control.
5. Incorporate quality improvement methods at the appropriate levels.
6. Integrate quality improvement methods at the appropriate levels.
7. Minimise the duration, cost and resources required to satisfy the needs of your customers.
8. Raise productivity levels.
9. Reduce time and effort spent on documentation.
10. Reduce overheads in general.
11. Track progress more accurately.
12. Empower the whole workforce.

The main task of engineers is to apply their scientific and engineering knowledge to provide a solution to a technical problem. This may derive from sales and marketing organisations within a company, seeing a potential gap in the market. Engineers will have to analyse these requirements, optimising solutions within them while being constrained by considerations which include material, technological, economic, legal environmental and human related issues. The influence of these constraints is getting more prominent in design and in the market place due to changes in environmental and customer requirements. In years past the customer had little choice and did not carry much influence on specification of the final product. A typical example of this was the Model T, where Henry Ford even denied the customer's freedom to choose the colour of their vehicles, famously saying, "You can have any colour, so long as it's black". In today's environment, comments such as these would be deemed as unacceptable and would be harmful to the further growth of the company. However, the Model T was born in 1908, 19 years and 15 million Model T's later the Ford Motor Company was a giant industrial organisation that spanned the globe.

In today's environment, fuelled with political agendas, design teams need to meet many requirements driven from the customer and market forces. These would include factors such as customers demanding more technically advanced products that are environmentally friendly. One good example of the development of this is the Mercedes S Class. If a car has a specific feature installed, and it is technological, then the chances are it started life in a Mercedes S Class. For example, advanced braking systems (ABS), airbags, satellite navigation and three point seatbelts all started their lives in the Mercedes flagship. Now there is a new S Class (2007), and it is starting to introduce the next automotive technical advancements. For example, it has digital television built in, a radar system which will allow the car to automatically follow the car in front, at a safe distance. It will apply the brakes when the car in front does, and accelerate when the gap between you increases. Some of the new safety features include:

- Night View Assist. This introduces two projectors, one mounted in each headlamp array; these project infrared light onto the road ahead, increasing the driver's forward view to approximately 500 feet.
- Distronic Plus; this monitors traffic ahead to help maintain the driver's selected following distance even in stop-and-go traffic
- The Dynamic rear view monitor; this help you navigate when parking, it has a number of cameras positioned on the vertical and the superimposed guiding lines appear on the screen and change according to steering wheel input to assist the driver with parking manoeuvres
- Brake Assist Plus as part of the Distronic Plus systems
- Adaptive braking

All this technical advancement has been introduced to the vehicle by the designers while minimising engine output omissions to ensure it complies and exceeds the requirements of the environmental policies and customer expectations.

2.2.2 Current Design Life-cycle Models

There are many different requirements that have to be met by the design team, and in broad terms there are core activities that have to be undertaken to ensure the robustness of the design. However, due to the variations in uniqueness of the products and their requirements, there are areas within the design life-cycle that can be tailored to aid these. There are a number of models which help deliver the initial concepts or customer requirements into a product to enable manufacture and sale to the customer.

2.2.3 Stuart Pugh’s Design Model

One of the classic models of the design life-cycle was developed by Pugh (1991), who believes that all designs start, or should start, with a need that, when satisfied, will fit into an existing market or create a market of its own. From the statement of the need, often called the “brief”, a product design specification (PDS) must be formulated for the specification of the product. The PDS acts as the control of the total design activity, because it places the boundaries on subsequent designs. From here Pugh’s design life-cycle goes on to introduce the different stages of the design to bring the product to maturity at its final stage of manufacturing. He also indicates it is essential for design to have a central core of activities, all of which are imperative for any design, irrespective of the domain.

There are a number of design models that are the basis of design processes in today’s industry; Pugh’s model is one of the best known and most extensive. He claims that one of the key roles of the designer is to pull together all the information required to enable the process to proceed to meet customer requirements.

Pugh’s design life-cycle consists of six main elements:

1. Market (user needs)

The starting point for any design should be to establish the market / user needs in considerable depth. A document should be produced at this stage usually referred to as the ‘brief’. This can vary from the simplest of statements to a comprehensive document that aptly describes the true user’s needs. Pugh, explains that unfortunately the brief lacks the detail required to ensure a good foundation for the product design ahead.

2. Product Design Specification (PDS)

As discussed previously the PDS is an essential part of the design process. In the design process, this specification is the basic reference. When the designer is designing a specific product they should be attempting to meet the specifications. This should be considered as an evolutionary, comprehensively written document. At the end of the design activity, the design of the product must be in balance with the PDS, even during the life of the design. Pugh strongly highlights that the absence of the PDS results in designs that will fail in the market place; poor PDS leads to poor designs, however a good PDS does not necessary lead to good designs but helps to make the goals attainable.

3. Conceptual Design

At this stage of the design life-cycle the primary concern is to generate solutions to meet the PDS. The concept design may be defined as the representation of the whole of the projected product; it presents the sum of all the subsystems and the components that go to make up the complete system. This phase can be broken down into two major components;

- The generation of solutions to meet the stated need.
- The evaluation of these solutions to select the one that is best suited to matching the PDS

This phase generates the ideas around the PDS, solving technical problems that may occur in the PDS. Discussing ideas with colleagues in the design team can be rewarding for engineers and it acts as a stimulus to the generation of further ideas and the refinement of existing ones. It also introduces communication between different disciplines within the design team.

4. Detail design

A good, sound detail design is as important in the over-all design activity as the conceptual stage. Pugh gives a constant reminder through his publications that all stages are of equal importance to the design process. He also states that a poor or indifferent detail design can ruin a good, even brilliant, concept and the reverse of this, he claim is also true.

When the engineers are in the detail design stage of products, the engineers need to harness their knowledge of materials, techniques of analysis, technology of simulation, environment of the product, quality, aesthetic appeal etc. He recommends that during this stage of component design it is important to list all the constraints that need to be considered so that the component itself fits correctly into the situation and environment of the product.

5. Manufacturing

At this stage the manufacture of the design starts to be considered and Pugh discusses the importance of Design for Manufacture (DFM). A design must exist before it can be made; Pugh claims that confusion and inefficiency may occur at this stage in the design life-cycle.

However, this is not a result of the product being manufactured after it is designed; rather that the manufacturing engineers have, traditionally, not been involved in the design until designers have completed their work. This lack of involvement from the manufacturing engineers can result in long cycle times from the completion of the design to the market place and will result in a number of outcomes:

i. Low quality products
ii. Late market release
iii. High cost products due to difficulty of manufacture.

6. Sales

There are two primary aspects to marketing in the broadest terms;

i. Establishing the nature and characteristics of the product to be made by means of market research; setting the users needs in context at the beginning of the design core.
ii. The marketing of the final product – distribution, service back-up etc., which are all part of the marketing or selling activity.

This sales role in the design life-cycle has to consider a number of aims; firstly, to ensure that the questioning of the customer is not a random affair; secondly, any mistakes that occur from the designing of products that do not meet the customers needs should be highlighted back to the design team. The selling stage of the design core completes the total design activity core model but this stage may differ according to the product, e.g. whether the product is a large one-off manufacture, such as a nuclear power station or a product manufactured in small/medium batch quantities. Each case will require the organisation to have different logistic support and a different approach to the business. In turn this will introduce a different type of interaction into the design life-cycle.

Later Pugh introduces further interactions into the initial design core. To enable the design to be developed the designer will require techniques for analysis, decision making etc. In conjunction with this, the engineer will need technological knowledge such as stress and fatigue analysis, thermodynamics analysis, information on material etc. At this stage, the designer has arrived at a broad design core, always enveloped by the PDS and with inputs from the various disciplines in the design process. He then places the structure within the framework of planning and organisation to produce the total design activity model. The detailed flow diagram shown in figure 2.1 shows Pugh's model and how these interactions take place, it indicates all the various levels of information that are required to be obtained through the product design phase.

Pugh introduces a classical design structure that a large number of alternative design life-cycles adopt. The importance of following a structured design life-cycle is clearly highlighted in Pugh's publications and the consequences that may occur if this does not happen are emphasised. However, the author's experiences in a modern design environment show that the designer generally follows a structure, but as the design matures and engineers start to answer technical questions arising from problems that develop through the design life-cycle, they instinctively start to move away from the process. Pugh clearly highlights the consequences of this. As engineers introduce their "*artistic license*" to the design, many crucial issues maybe overlooked and a potential snowball effect of errors may occur. With this in mind there should be a clear enforcement of the design life-cycle, and before the design can progress and mature through the life-cycle, clear well defined gates should be passed to ensure that the engineer has not merely looked at the design in isolation without consideration of the product as a whole. The solution to this is discussed in chapter 5.

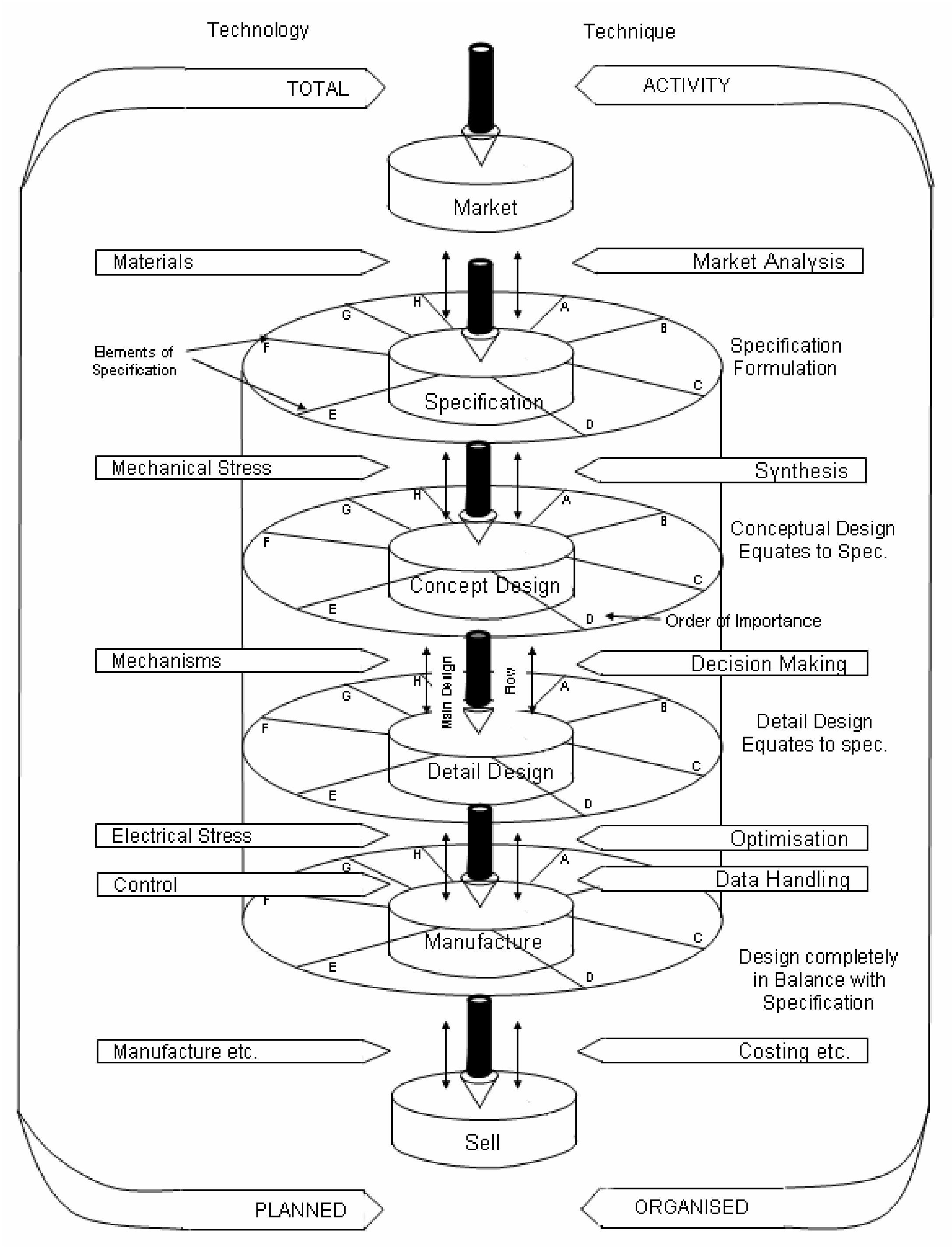

Figure 2.1 Total Design Activity Model (Pugh 1991)

As the product starts to get more complex, as in aircraft manufacture, there will be many interactions in and out of the design life-cycle. These can bring further potential problems to the design and although Pugh discusses additional complexities in his work it is limited by not having a structured approach to the solution of these potential problems that occur in the design of high complex products. The model VDI2221 is an example with a systematic approach in the way it deals with complex technical issues in design.

2.2.4 Verein Deutscher Ingenieure (VDI 2221) Model

Wright (1998) claims that this model is the best attempt to introduce project complexity or size in the design process. The Verein Deutscher Ingenieure (VDI) is the professional body of German engineers, and the VDI 2221 is their guideline for a systematic approach to the design of technical systems and products.

This approach looks at the information, the issues of size and complexity of the design process that need to be taken into account. The VDI 2221 model attempts to illustrate this in Figure 2.2 This guideline recognises that complex problems are not solved as a whole but are broken down into a number of sub-problems that are solved individually, basically breaking the complexity of the design into less complex portions. Wright describes how the process works. The general progression of the design process is downwards through the five plans. The overall design problem is broken down further into individual problems which, in turn, combine to form an overall solution to the problem. If a viable solution to some individual problems cannot be found, it may be necessary to go right back to the overall problem definition to examine if all of the objectives and constraints are valid. When sub-solutions are combined into the overall solution, it may be found that overall systems performance is not satisfactory, despite the care that was taken in evaluating sub-solution performance. This may necessitate reworking several previous stages of the design process.

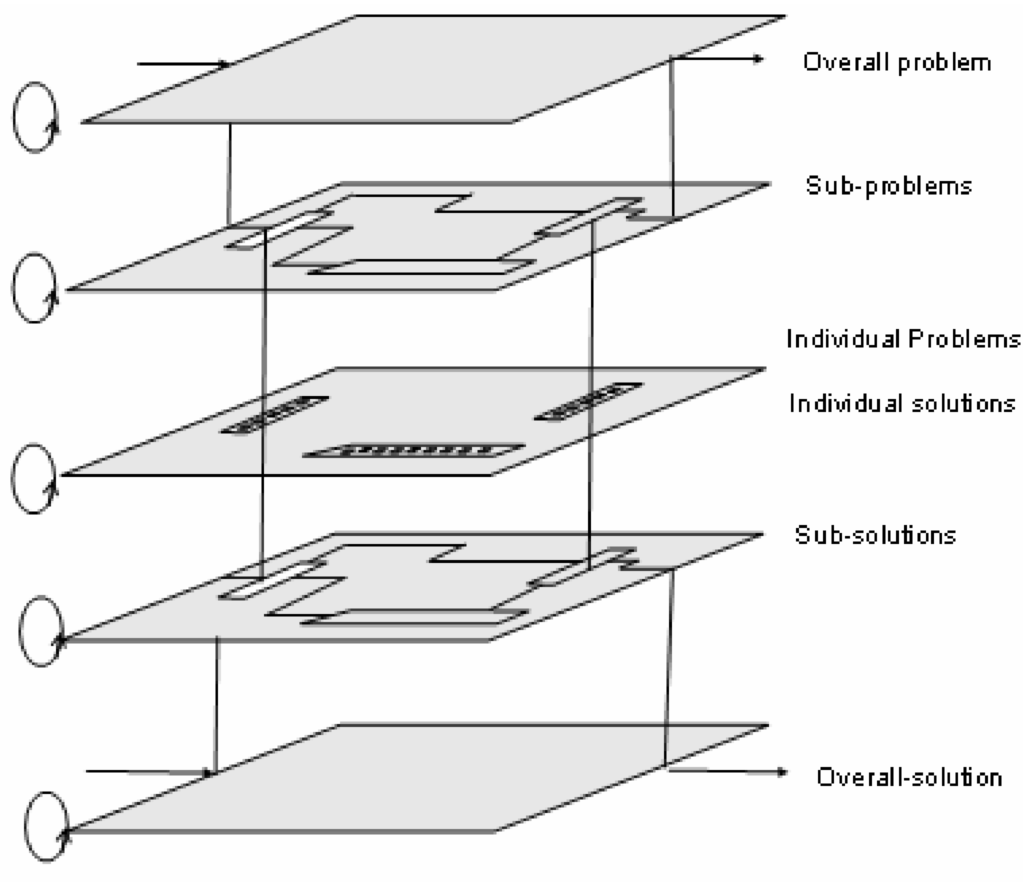

Figure 2.2 – The VDI Model with iteration loops, Wright (1998)

Wright (1998) discusses the problems that occur when in the product design phase and the inability to move the design forward without complete data from every required source. This point that Wright makes is a valid one in today's industry. It is important to accommodate this in the design life-cycle as it is crucial that the design meets the market at the correct time in the overall life-cycle. In other structured design life-cycles discussed, there is minimal attention to this, the current models may suppress the progress of design entering into the market. Wright introduces a good example to highlight this issue. In a gear design there are various requirements that are needed; gear calculations, bearing calculations and shaft calculations. These equations describe the behaviour of gears, shafts and bearings and are well known and tangible. However, the size of shaft cannot be calculated until the gear design has been progressed to a stage where the separation and axial forces are known. There are many other decisions like this that need to be established for the progression of the design. The problem is the process gets trapped in a circular rotation without sufficient knowledge to determine a starting at a point in the process. The way forward is too *'cut and dry'*; this takes one's best shot at assigning starting points in the process. The potential issues in the 'cut and dry' theory can be:

- Is the information / calculation correct?
- How long will the process evolve before the wrong calculation is detected, if ever?

The best mix for this would be engineering experience with similar problems, this is obviously a considerable advantage because it improves the chances of the first '*guess'* being closer to the final solution.

This illustrates how complex the design process can be. In the vast majority of cases, each of these iterations will require information from multiple sources and the involvement of many people to innovate, evaluate, analyse and make decisions. A potential solution to this is discussed in chapter 5, showing how the design life-cycle can be structured to control this issue

2.2.5 Acar's Triple-helix model

The previous models look at the general progression through time in the design process. Acar's (1996) triple-helix model of the design process shows the views of the activity through the eyes of those involved. As time passes, the product development passes along the helix, but at any given moment a slice through the helix shows that there is always interaction between the three aspects of the process, specification, embodiment and concept design. He also starts to introduce complexity and issues that may occur during the design process, along with the introduction of the experience of the engineer, as discussed previously this can be extremely valuable to the progression of the design, however it is difficult to control in a structured design environment. As engineers generally have a trait to solve technical problems that occur in the design of a product as they arise, they can easily move away from the design requirements and end up producing an over elaborate solution. Acar starts to look at some of the issues in the design life-cycle, discussed previously; this is illustrated in his triple-helix design process in figure 2.3.

2.2.6 French Design Process

French (1998) also discusses the importance of the designer's experience in the design process. He claims he has a clear view of what design methods cannot do and probably never will be able to do. They cannot replace the gifts of a talented designer, nor provide step by step instructions for the production of experienced designers. What design life-cycles do is to improve the quality and speed of a good designer, and increase the size and complexity of tasks they can tackle. He also suggests that they can speed the development of a young designer and improve the co-ordination with essential specialists inside and outside the design organisation.

French highlights a number of areas that a structured design method would help:

- By increasing insight into problems, and the speed of acquiring insight.
- By diversifying the approach to problems.
- By reducing the size of mental steps required in the design process
- By prompting inventive steps, and reducing the chances of overlooking them.

- By generating design philosophies (synthesising principles, design rationales) for the particular problem in question.

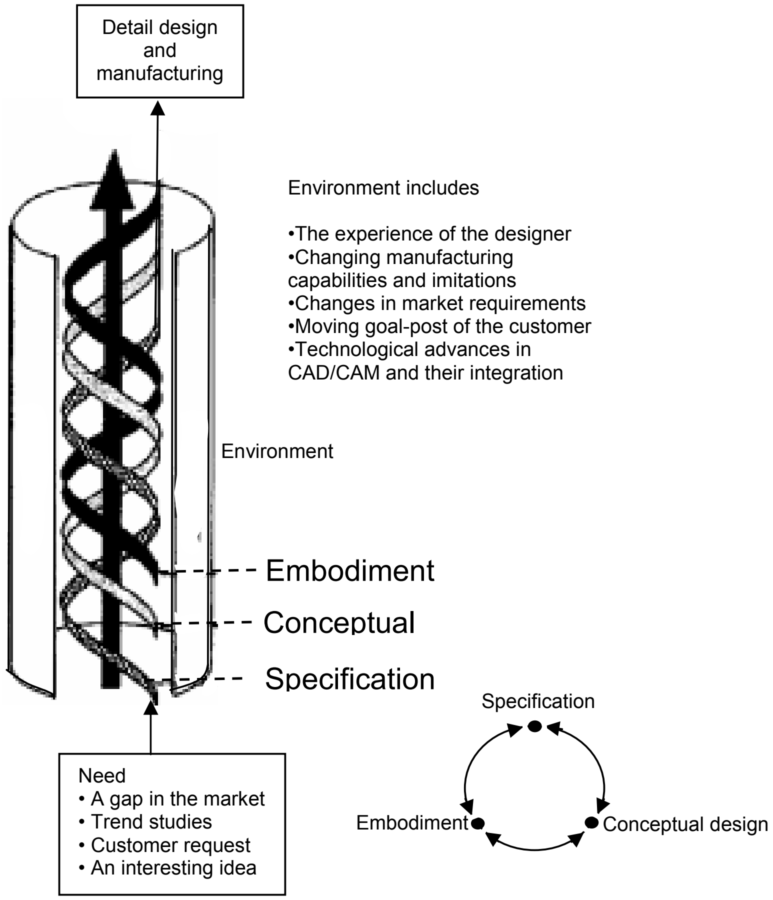

Figure 2.3 – Acar's triple-helix model of the design process, Acar (1996)

French (1971) introduced an eight stage design process that will help develop and produce a robust design. These stages are discussed below:

1. Determination of customer requirements

This looks at what the customer requires. There are a number of tools that can be used to establish these requirements ranging from simple communication to the customer to more structured tools like Quality Functional Deployment, (discussed later in this chapter). Cost time scales and functionality should be included in this stage of the design.

2. Product design specification

This stage is to convert the non-technical, non-quantified customer requirements into a set of product characteristics expressed in engineering terms. This should set out the requirements in as complete a manner as possible, and include the development of more formal engineering specifications, where necessary.

3. Initiation of concept solution for further development.

Here the design team can commence the innovative activity of proposing product configurations to satisfy customer needs. A number of alternatives attributes will be defined here; the more there are the more likelihood to find the appropriate attributes.

4. Selection of the best concept for further development

The output from the concept initiation stage should comprise a number of alternative product configurations. In some of these cases there may be a compromise as one alternative may address one customer need and another alterative may address further requirements. Making the correct decision at this stage is vitally important.

5. Embodiment design

During this stage the designer needs to think in more detail about many aspects of the design concepts to enable a full evaluation to be made, many of the final decisions will only be made during embodiment.

6. Detail design of chosen concept, and preparation of full manufacturing descriptions

Detail design is concerned with providing a description of each component and all elements of the product. All the information must be given in sufficient detail and in such a way that the product can be manufactured without any ambiguity.

7. Manufacture.

The manufacturing stage is where the design starts to be manufactured and any error during the previous stages will be identified here.

8. Sales and support

At this stage the manufactured product enters the market place, and customer feedback may arise, which must be taken into account in any re-design.

The above information again highlights a structured design life-cycle. In real-life there are many other interactions and complex communications in this process with different levels of the life-cycle and disciplines. Given these additional factors to the above life-cycle French introduces additional feedback loops; this is illustrated in Figure 2.4.

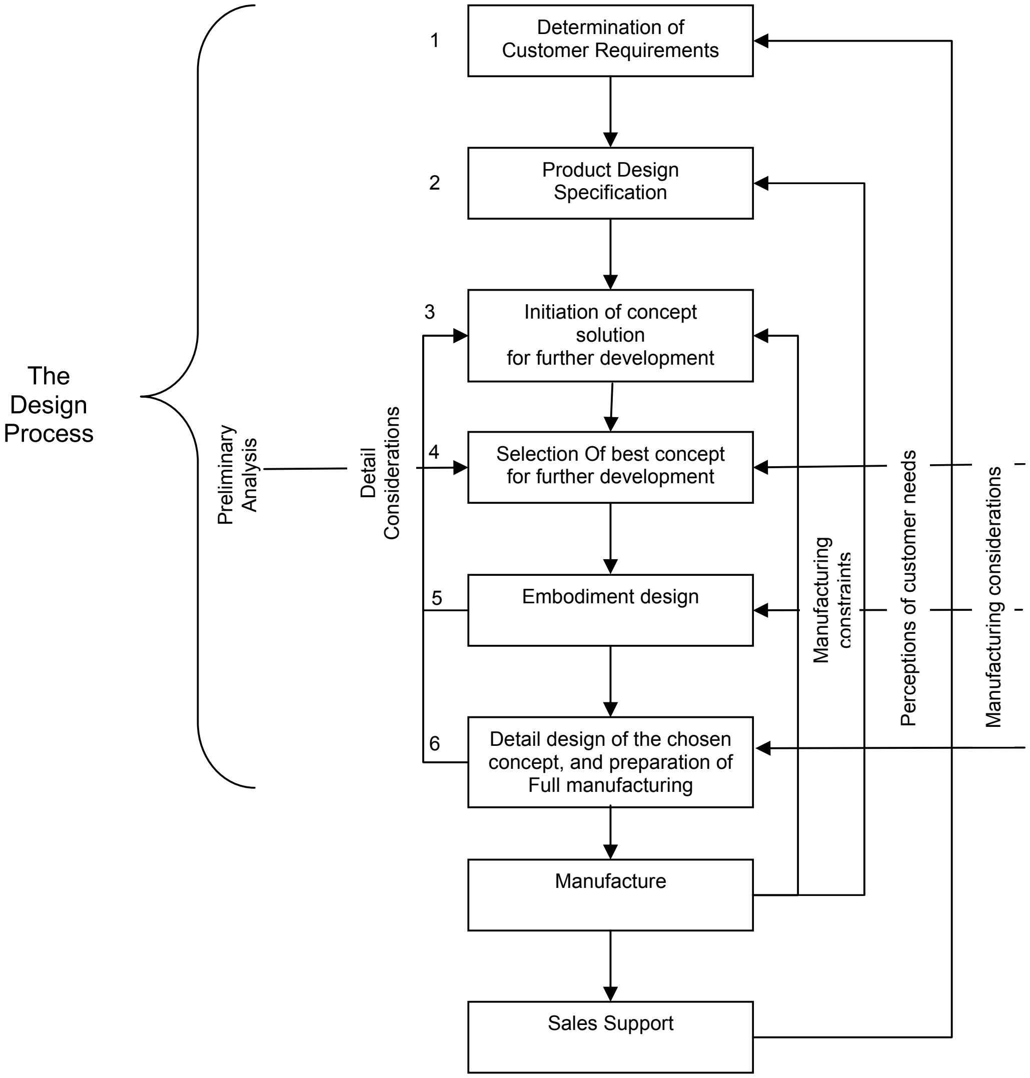

Figure 2.4 – The design process with 'feedback' loops, (French 1971)

2.2.7 Boothroyd and Alting six phases

So far within this section the main focus has been on the design core, this is a central part to most design life-cycles. However there are many interactions to this main core one of the most prevalent ones being design for manufacture (DFM), this is discussed in more detail later in this chapter.

Boothroyd and Alting introduce the importance of design for manufacture, particularly design for assembly, into the design life-cycle, (Boothroyd and Alting, 1992). They discuss that the final cost of a product is largely determined during its design and designers must take into account manufacturing from the outset. In many organisations there is an "over-the-wall" attitude to design, meaning the designer throws the drawings over the wall into manufacturing, leaving the manufacturing engineer to address the problems created by the designer without their assistance.

They also discuss the importance of the environmental needs of products and the rapidly growing concern for environmental protection. Therefore when designing a product it is not acceptable to think only of the functional aspects of the design but also the environment issues must be taken into consideration. With this in mind they claim that a new approach is necessary in the design of products to solve the many problems related to their production, use and disposal. There are interrelated issues in the design life-cycle. When considering design for disassembly it must fulfil the requirements of production, distribution, usage, and disposal or recycling. Therefore it is not sufficient to consider recycling alone as the goal, all the phases must be considered simultaneously. The interrelated issues in their design life-cycle are listed:

- Need

  This looks at the needs for the product.
- Design Development
  - Product Specification
  - Design principles; product structure, Functional unit and materials,

design guidelines manufacturing, assembly, distribution, usage (service and repair), disposal and recycling.

  - Assessment of consequences on environment, occupational health and resource utilization.
  - Life-cycle cost
- Production
  - Production Systems; processes, joining and assembly, automation
  - Energy utilization
  - Material utilization
  - Environmental and occupational health issues
  - Organisation
  - Production costs
- Distribution
  - Distribution principles
  - Transportation processes
  - Energy Utilization
  - Environmental and occupational health issues
  - Product structure (Size, weight, packaging unit)
  - Disassembly during transportation
  - Distribution costs
- Usage
  - Usage functions
  - Maintenance (repair, service)
  - Energy Consumption
  - Material consumption

  - Environment and occupational health issues
  - Usage costs
- Disposal / Recycling
  - Recycling market, structure, organisation
  - Re-use
  - Re-manufacture
  - Dismantling; Functional units, material, incineration, dumping
  - Recycling processing
  - Energy issues
  - Environmental and occupational health issues
  - Disposal / recycling costs.

These life-cycle phases are considered simultaneously from the conceptual product design stage through the detailed design stage. This process is illustrated in Figure 2.5, where the selection of technical solutions should be guided by criteria containing the main elements shown in the outer cycle. Namely:

- Environment
- Protection
- Working conditions
- Resource utilization
- Life-cycle costs
- Manufacturing properties
- Product Properties and company policy.

In this approach policies must be established for environmental, occupational health and resource issues as well as for the disposal or recycling of the used products.

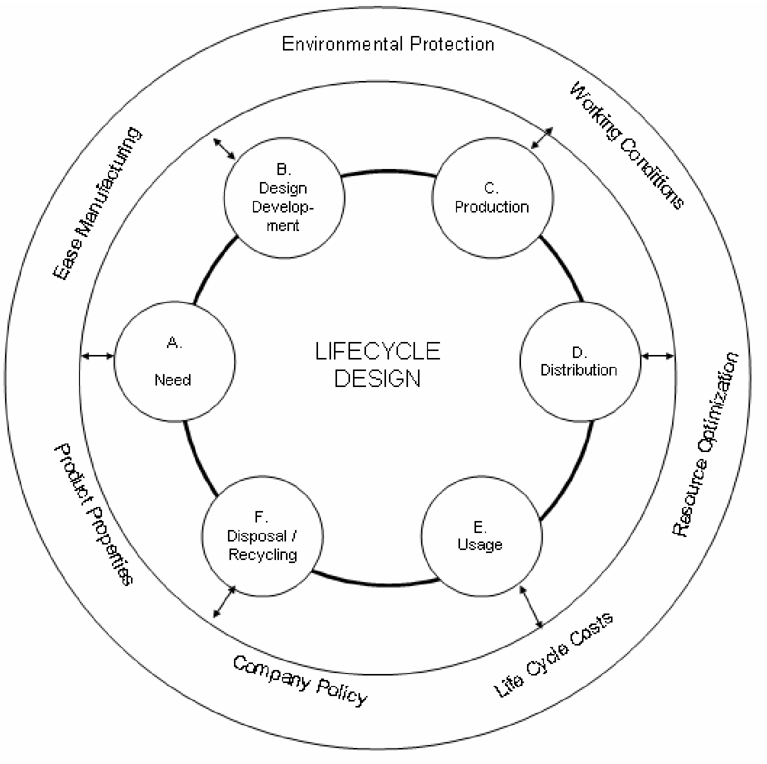

Figure 2.5 - The Life-cycle design concept, Alting, Boothroyd & Alting (1992)

2.2.8 Daimler-Benz Life-cycle

The Daimler – Benz method of life-cycle analysis, Weule (1993) describes several steps during the life-cycle of a product. The principle is to balance all-important data for technology, ecology and economics of a product to establish the impacts on the environment. This cycle begins with the generation of raw materials and energy, followed by the production process and the product use. It is completed by evaluating materials, recycling and waste management of the used product. As shown in figure 2.6 for every stage the impact on the environment has to be evaluated.

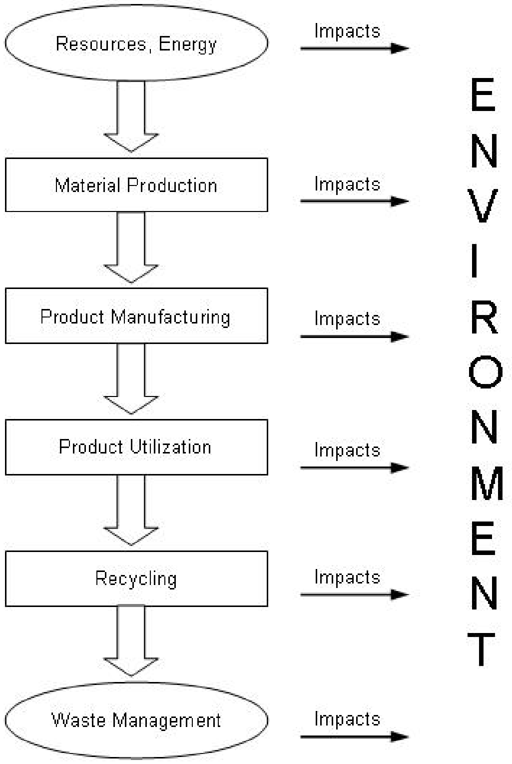

Figure 2.6 – Principle of life-cycle-analysis, Weule 1993

2.2.9 Pahl and Beitz, Seven phase Life-cycle

Pahl and Beitz (1996) propose a seven life-cycle phase. Their design life-cycle introduces more external factors from the various engineering disciplines that contribute to the design. In particular those of manufacturing engineering, with the introduction of production planning, manufacturing and maintenance and support. They also start to introduce the '*how*' in their work with various methods such as selection and evaluation methods, methods for finding and evaluating solution, techniques like brain storming are introduced etc. The seven phases are:

- Requirements Definition (RD)

To start the design process an idea is required that will lead to a technical and economically viable product. This will involve product planning, through the design and manufacturing departments while watching over its fit to market requirements. It may be necessary to clarify the task in detail before starting product development. The purpose of this clarification of the task is to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance. This activity will eventually turn into a requirements list that focuses on the design process and its subsequent working steps

- Conceptual design (CD)

In this phase of the design the team will start abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining the principles into a working structure. The results from this will be the specification of principle. Before the design can develop material selection, producing a rough dimensional layout and considering technological possibilities need to take place. This phase can consist of several steps, none of which may be skipped if the optimum principle solution is to be reached, in the subsequent embodiment and detail design phases it will be extremely difficult to correct fundamental shortcoming from this phase.

- Embodiment Design (ED)

During this phase, designers start from a working structure, determining the overall layout. A viable product concept from this phase is enhanced into more clearly defined forms. The results of this phase will be the product specification layout. Some critical dimensions, preliminary forms and sizes are specified. This definitive layout provides a check of function, strength, compatibility etc. and it is also at this stage that the financial viability of the project must be assessed, only on the completion of this should work start on the detail design phase.

- Detail Design (DD)

This is the phase of the design process in which the arrangement, forms, dimensions and surface properties of all individual parts are finally laid down. The materials are specified, production possibilities assessed, costs estimated and all the drawings and other production documentation is produced. The result of this phase would be the product specification. Often corrections must be made at this stage and the proceeding steps repeated, not so much with regard to the overall solution, but more for the improvement of the assemblies and components. Pahl and Beitz (1996) suggest that the crucial activities in this field are:

Optimisation of the principle
Optimisation of the layout, forms and materials
Optimisation of the production.

- Production Planning (PP)

This phase of the design life-cycle starts to develop process plans; routings and specific process parameters are specified. Decisions on outsourcing versus in-house production decisions are made. Machine tool programming occurs, cutting tools and featuring decisions have to be refining along with the generation of inspection instructions and production procedures. Also quality control, logistics, purchasing and capacity issues are addressed during this phase of the design

- Manufacturing (MFG)

Replicas of the product are built using the methods and procedures defined during the production planning phase. Production data is collected for analysis and engineering changes to the product are incorporated as necessary to meet the product speciation.

- Maintenance and Support (O&S)

Both planned and unplanned maintenance is performed on the product upgrades and engineering changes are implemented when required. This is particularly important for complex products with an extended life-cycle.

2.2.10 Discussion

The design life-cycle models discussed in this chapter, have central core activities on which the design process is based, Pugh introduced this approach. From the central core, the information flows between and into the different levels trying to control and structure the information entering into the design. Pahl and Beitz propose a seven life-cycle phase where each phase is often not totally completed before the next phase begins, with several phases underway simultaneously. Boothroyd and Alting’s six phases state that clearly, a new approach will be necessary in the design of products to solve the many problems related to production, using their design lifecycle to set a framework to introduce design for manufacture concepts. The Daimler – Benz method of life-cycle analysis describes the several steps during the life-cycle of a product. The basic principle is to balance all-important data for technology, ecology and economics of a product to establish the impacts on the environment.

Although these design life-cycle concepts strive for different outcomes, they have common boundaries in a structured design process. The research in this area highlights a number of potential areas for the introduction of novel proposals in the design life-cycle; in particular in the manufacture of high complexity low volume products, as in the aircraft industry. It is clearly important to adopt a structured method when designing a product, however the current design models, although highlighting complexities in the design process, do not handle this in a structured way to obtain a robust design. Importance of the engineer's experience in the design process has been discussed and how it can aid the flow of the whole process. However there has not been a structured conclusion to this on 'how' it should be introduced into the design. French himself makes the statement that "design life-cycles cannot replace the gifts of a talented designer". French (1998)

Within the aircraft industry, this information flow exists in a greater and more complex range; this is discussed in more detail in subsequent chapters. It is not merely satisfactory to control data, as the current design life-cycle models highlight. It needs to be compressed into a short time scale and to introduce DFM concepts to reduce costs, along with maintaining a structured process for the design. Another main observation from the current research is the lack of attention to the customer requirements and how the design meets these through the maturity of the designed product. This work aims to introduce these areas into a new novel approach to the design life-cycle of aircraft manufacture, with the emphasis on how DFM can be structured and measured into the design ensuring a robust design, while keeping the emphasis on what the customer requirements are and how close the design is to these through the design process.

2.3 Design Environment

2.3.1 Introduction

The previous section discussed the design life-cycle, where the main context of the design is developed, however this operates in a design environment. The design environment is the global environment in which an integrated product team (IPT) and the design life-cycle operate, structuring the way the engineering activities are established and developed. This environmental aspect of the design has become more prevalent in the current environment, especially in the aircraft industry where new products have become too costly for a single organisation to afford. New products like the Airbus A380 (Airbus Industries, 2006) and military program F35 (F-35 Joint Strike Fighter Program Office, 2006) have multinational teams that span the globe. This increases the problem issues in an already complex product. It is therefore important to look at the design environment that this operates in. The following section will introduce the reader to the main design environments prevalent in current academic work, within the aircraft industry.

2.4 Design Environment models

The context of this literature will be drawn from the work carried out by Yazdani and Holmes (1999). They investigated two major industrial sectors, aerospace and automotive in order to establish the main types of design definition environments practised in these industries. This study spanned over three years, covering six automotive and two aerospace companies, the main parameters considered in their work were:

- New product introduction driving forces and measurements of performance. This involved interviewing the senior management of the companies to identify and rank the factors and criteria employed in each firm.
- Risk; this was measured in terms of technical and commercial risks for both incremental and breakthrough products.
- Time; they investigated lead time, critical path from project launch, concept approval, to volume production.
- Cost; this was measured in terms of project cost throughout the process.
- Quality of the design; this was measured in terms of cost of engineering changes and also the stage at which change was necessitated.

The outcome of this research was four design environment models. After reviewing the research background and methodology of Yazdani and Holmes' work, in the context of this research it seemed appropriate to base this section around the four models that their results developed.

2.4.1 The Sequential Model

The sequential model shows the traditional functionally based organisation where the design definition of the product is established and then all the disciplines add their input to the design in a sequence of activities until the final design output is achieved. This traditional model of development has proved not to be satisfactory for today's industrial pressures where cost, quality and time parameters are far more demanding than ever before (Stalk and Hout, 1990). The information here is batched at each stage and passed onto the subsequent activity, similar to that of design to build, and so on until production is ready. Yazdani and Holmes', diagram shows clearly how the information is past through to each phase and then returns back to the start of the cycle until the optimum is achieved; this is shown in figure 2.7. The approach has an effect on design changes, which is a key and underestimated role, especially in the complexity of the aircraft industry. The process is constantly reviewing the change of the design through each stage. The main concern with this would be the potential time span involved to keep up with this constant change process, potentially delaying the launch of the product into the market. The type of organisation that uses this style of design environment would be a functionally based organisation, where it is managed by discipline rather than by the products.

The investigation found that the driving forces within companies that employed the sequential model were determined to be predominantly based on cost and quality in the automotive sector, and technology in one aerospace firm.

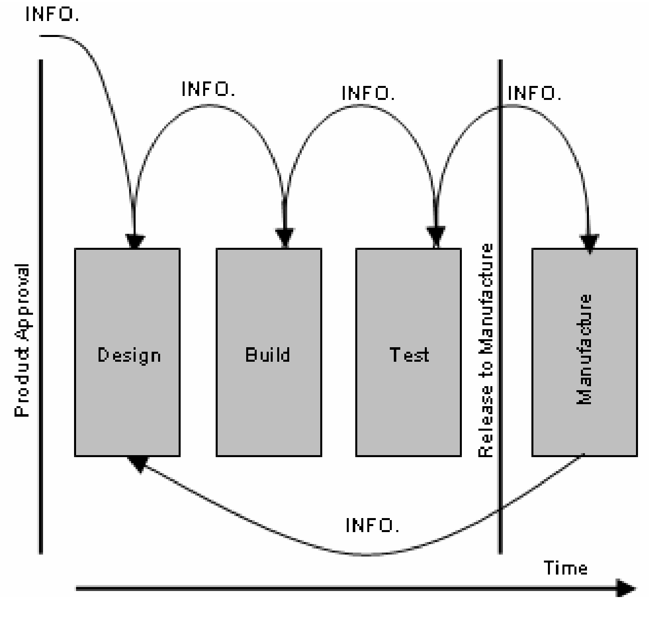

Figure 2.7 – Sequential engineering, Yazdani and Holmes (1999)

2.4.2 The Design Centred Model

Yazdani and Holmes found that many companies realised that the cost of change at each sequential stage proved to be very expensive. With this in mind a whole set of tools were developed in order to identify necessary changes and control them. The potential tools used are discussed by Prasad (1996), and the technologies here are centred on these tools such as finite element analysis, design for manufacture, design for assembly, design for environment, life-cycle costing etc. These tools help to reduce change in the design process, although they will not totally eliminate it. The tools are merely an aid to the design process. The change control process is the same as the sequential model in that the master model requires modification to enable engineering change to occur. The premise of design centred design environment is that at each stage risk is minimised before release.

The design centred model demonstrates the front end fixing of the design. In this environment, the design methodology dictates that there is a higher level of design analysis required at the front end of the process, Yazdani and Holmes' diagram shown in figure 2.8 illustrates how this process works. This design environment does not always require the involvement of various disciplines; instead it is considered that their involvement is embedded in the activities in the detail design, with the result of the minimisation of downstream change. To ensure that interaction between disciplines was maintained Yazdani and Holmes, found that there tended to be a 'lightweight' project coordinator who introduces the liaison between the disciplines involved in the design life-cycle. They concluded that this environment was observed in most western-style engineering companies, particular aerospace, where life-cycle analysis has traditionally been a requirement from the customer. The main driving forces with the companies of this environment tended to be that of quality and cost of development.

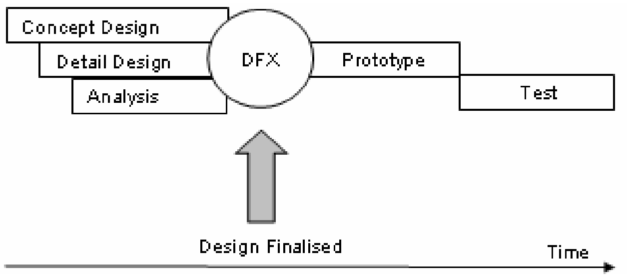

Figure 2.8 – The design centred model, Yazdani and Holmes (1999)

2.4.3 The Concurrent Definition

The concurrent definition model introduces the concept of concurrent engineering and stage gate systems, with the design definition being fixed at various gates in the process. Each stage of development has a gate attached, which all downstream activities have to pass through in order to allow the continuation of the master design. The previous environment brought about a more robust design by improvements in cost reduction within this environment. However, within industry that is a continuous drive to reduce the overall lead times during the design life-cycle Channon and Menon (1994) discuss this. Within this concurrent environment, downstream actives bring the specific expertise into the design phase. One of the key differences that is present in this current environment other those discussed previously is the overlapping of design and the planning of the process development, Yazdani and Holmes illustrate this in their diagram (figure 2.9). Here, each phase has a gate attached, which has all the downstream activities represented in order to allow the continuation of the design. In their publication they claim that DFX tools, discussed further in section 2.5.1.1, can be used but they are not essential as the expertise of the downstream activities is present in the multi-functional team responsible for allowing the project to proceed at the gate review.

As discussed in all of the design environments in this section, change plays a key role in both the design life-cycle and the environment in which it operates. With the nature of the concurrent environment the change process becomes more ambiguous, forcing incomplete design data between each stage in the design life-cycle. This needs to be carefully managed as the lack of control of change may have an adverse effect to slow down the design life-cycle, the opposite to what the design life-cycle is trying to achieve. Yazdani and Holmes conclude that with this environment the organisational structure needed to have focus towards the team approach, with few layers of management and the decision-making responsibility shifted into the project team. They found that teams were normally led by a 'heavyweight' project manger, as discussed in Hayes and Wheelwright (1988). They found that this approach was found in the automotive industry, Rover and an aerospace system supplier, to support the reduction in lead-time.

This design environment seems to have a good effect on the overall product in terms of cost reduction, quality and lead-times. Yazdani and Holmes, seem to have missed these areas in their research. Holmes (1994) looked at the concurrent engineering environment in Boeing's development of its new 777, in which the adoption of this environment formed part of their radical departure from the traditional design environments. In his work he found different disciplines pulling in different directions and from this he highlights the importance of a decision maker who decides on the route for the progression of the design even if the team are not in total agreement on this. He also concludes that there is still further work to be done in this area. In the work of Hauptman and Hiriji (1999), they looked at a sample of 50 cross-national concurrent engineering project teams. This extensive piece of research found a number of unexpected but potentially interesting finds:

- The negative relationship between readiness to use incomplete and uncertain information and democratic project leadership styles.
- The positive relationship between readiness to use incomplete and uncertain information and differences between the design/engineering and manufacturing representatives.

Haque (2003) looks at problems in the concurrent environment through the use of three in-depth case studies. The research work highlighted the importance of process management, with a focus on process modelling and analysis of the organisational factors, to improve the existing implementation of a concurrent environment. In general, the key problems for all three companies were integration, particularly between design and manufacturing functions, and inappropriate leadership goals and communications both vertically and horizontally across functions. The lack of true cross-functional process understanding and knowledge was one of the main reasons for this. Figure 2.9 illustrates the interaction in the concurrent definition model.

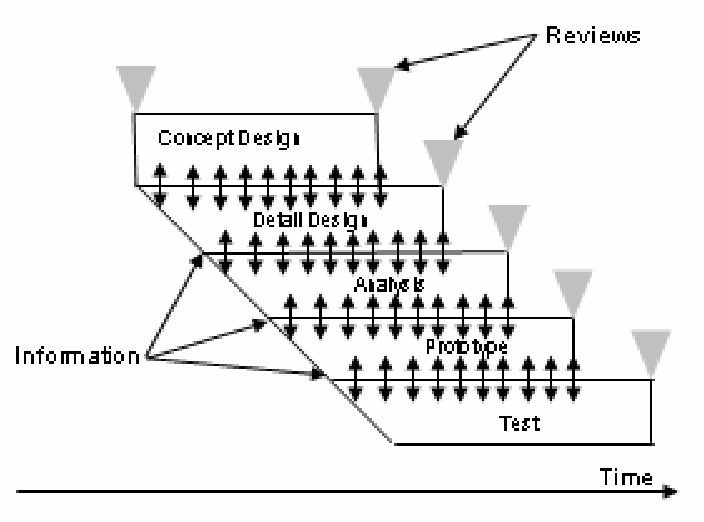

Figure 2.9 – The concurrent definition model, Yazdani and Holmes (1999)

2.4.4 The Dynamic Model

The dynamic model demonstrates the interaction of the various functional skill groups and shows a radical departure in the way the design information is transferred in complex organisations. It further develops the concurrent environment by ensuring that a much more intensive level of communication is present from the start of every program. This allowed a greater time constraint to the design stages, hence becomes much more concurrent as all the activities start at the same time. Yazdani and Holmes' diagram highlights this in figure 2.10. The constraints of the concurrent environment may be highlighted in this environment due to the amount of upfront design work required. They highlight that in order to enable the intensive exchange of information; a greater degree of integration is required where all the functional tools and techniques need ability to seamlessly exchange engineering data. The data is finished at the review point. This becomes the master model for the next phase of the development cycle.

Change management in this process becomes very much simplified; this is controlled at the product and process levels. Hence, with this there is a greater emphasis not only on their technical skills but also on their business and project management skills to enable them to make the correct decisions for product progression. However it was found in their research that if the decisions where not taken at working level, the technical risks will outweigh the benefits gained from this dynamic environment; Yazdani (1997) discusses this. They found this process working well in the automotive industry, and it can only be possible in a very flat organisation structure such as that of Nissan where they operate a four level worldwide structure.

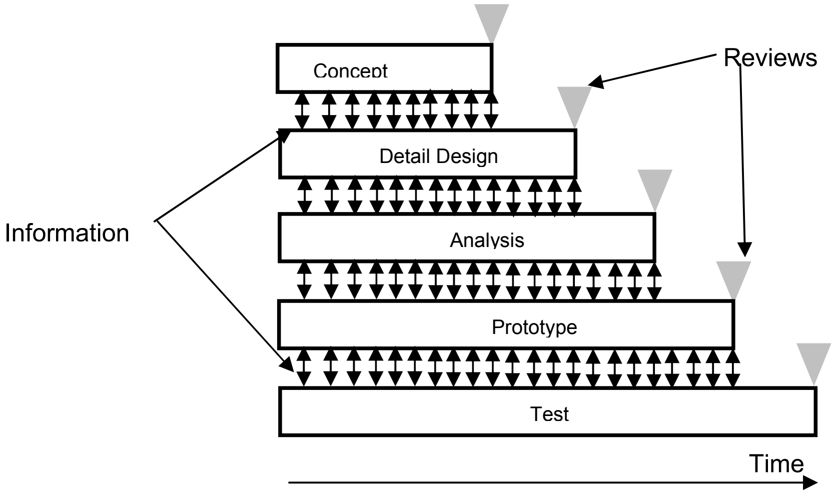

Figure 2.10 – The dynamic model of design definition, (Yazdani and Holmes, 1999)

2.4.5 Discussion

The above section has discussed current research in the design environment. One area that it needs to be distinguished is the separation between the design life-cycle and what many researchers call the design definition. There is a clear division between the two. Firstly the design life-cycle is the specific detail steps that a product should undergo to achieve a robust design. It was identified previously in this chapter that these steps need to be clearly used to ensure the best technical engineering answer is achieved. Secondly there is the environment in which the design life-cycle operates. This encapsulates the design life-cycle and is dependent on the environment selected and will depend on the order the design life-cycle is used. For the purpose of this research the two have been separated. However once the environment has been selected the two are combined to produce an overall design structure. As there are many advantages and disadvantages for each environment, chapter 5 introduces a novel environment selection tool, to aid an organisation to select the most appropriate environment for the design life-cycle to work in.

2.5 External Factors to the Design Life-Cycle

2.5.1 Design for Manufacture

Design for manufacture (DFM) is designing products with manufacturing in mind. It may help to understand DFM if we look at how a designer would design a product without consideration of DFM at all. Boothroyd & Alting (1992) discuss how the design culture created "*we design it ……. you build it*" mindset. This attitude has now come to be known as "*over the wall*" design. These comments can still be heard in today's design environment when designers are questioned by manufacturing engineers. The meaning of this is that the designers throw the design over the wall to manufacturing without interfacing with them, leaving manufacturing engineers to deal within the problems of the design when they arrive. A designer will design an assembly with a sequential approach, for example, ensuring all the parts go together, the design being fit for purpose. This potential for poor design can have a negative effect on product cost, however. A good manufacturing engineer will have a good understanding of the manufacturing difficulties that can occur when assembling a product, e.g. access to components installation, fastener access, reduction in the quantity of parts, designing in integrated features on components to aid part location etc. A scenario can easily be developed where designers may rarely, if ever, engage in manufacturing due to their work loads and constraints in the design office. The goal is to reduce costs required to manufacture a product and improve the ease with which the product can be made, Korngold and Luscher, (2000).

Bralla, 1999 highlights that the concept of DFM is not a new one, it dates back as early as 1788 when LeBlanc, a Frenchman, devised the concept of inter-changeable parts in the manufacture of muskets which where previously handmade. By implementing limited tolerances on the components and developing basic manufacturing processes for repeatability, the muskets could be made far more quickly, cheaply and reliably then before. However, it was not until the late 20th century that the term DFM became a 'household' name in industry.

As discussed, poor design can potentially introduce excessive cost into the product. The cost of the product includes the design cost, the manufacturing costs, expenses associated with product warranties and engineering re-design. Korngold and Luscher (2000) break these manufacturing costs down into three categories:

- Labour (direct and indirect): 2-15% of the total.
- Materials and manufacturing processes: 50-80% of the total
- Overheads: 15-45% of total

From this Korngold and Luscher suggested that current research indicates that although design costs consume approximately 10% of the budget, typically 80% of manufacturing costs are determined by the design of the product. Therefore, as discussed previously, no matter how creative manufacturing engineers and production managers are, they cannot influence the manufacturing cost of a product by more than 20%. Therefore, the *"over the wall"* environment adopted by some designers will severely limit the reduction to the overall product costs.

O'Driscoll, M. (2002), introduces a typical DFM workflow, shown in figure 2.11, claming that DFM avoids redesign and cost pitfalls, discussed previously, through the integration of the following activities:

- User needs and requirements.
- Market forecasts, projected sales volumes, unit price and demand.
- Product development process (including concept, definition, development of prototype and testing phases).
- Component design, subassembly design, and assembly analysis.
- Quality requirements.
- Process selection, materials selection and suitability.
- Economic analysis and cost evaluation.
- Design feasibility, investigations and redesign.
- Production and commercialisation.

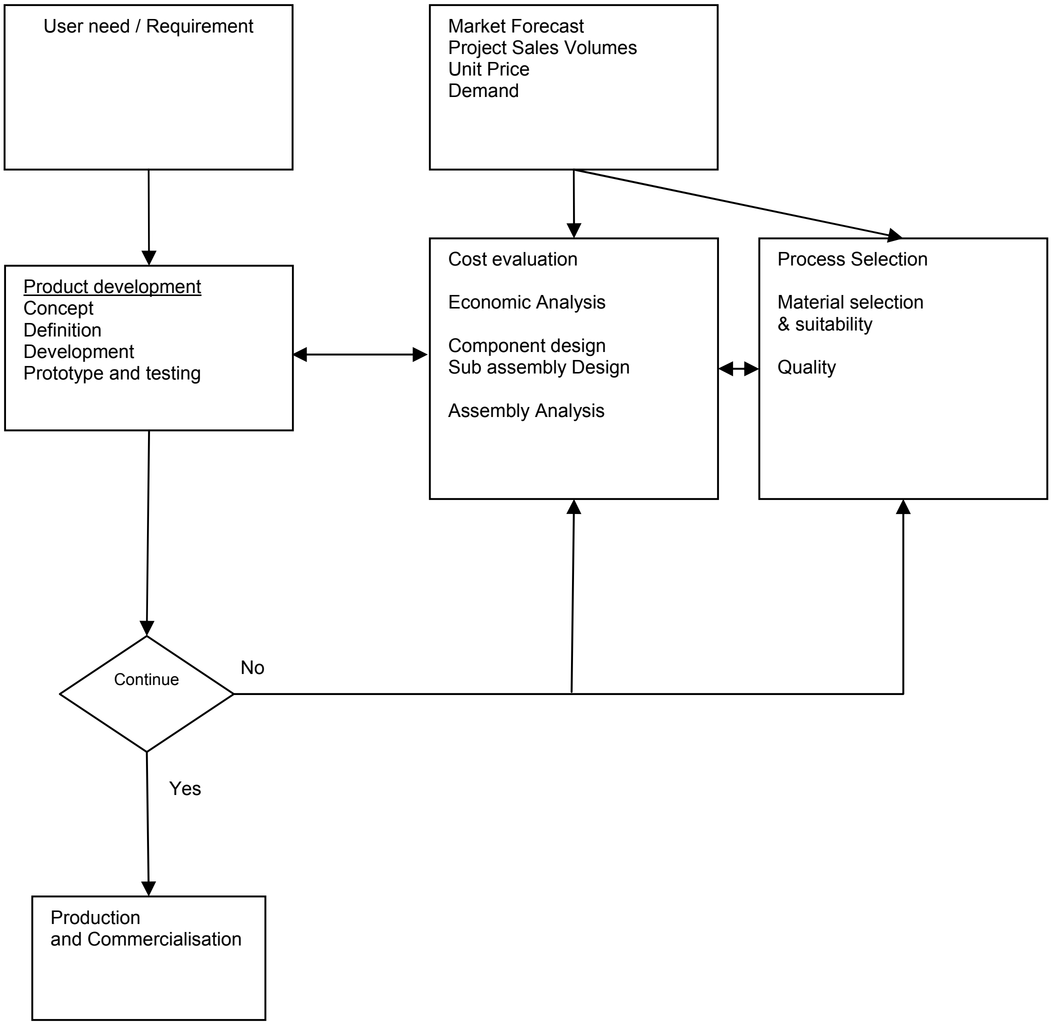

Figure 2.11 – Typical DFM flowchart (O'Driscoll 2001)

Boothroyd looks at DFM in the area of assembling products, he claims by studying the design carefully in assembly you can significantly reduce the overall cost of the product. Boothroyd (2001), discuses that many engineers mistakenly assume that an assembly costing of several simple components is less expensive to manufacture than a simple complex part and any assembly costs more than offset the saving off the individual component costs. Boothroyd claims that this is wrong on both assumptions, taking the assembly costs into account and ignoring storage, handling, quality and paperwork costs, the design is 50% more costly than the single complex product. In the DFM field, DFA, discussed further in section 2.5.1.1, has generated a revolution in design packages, Boothroyd claims, not principally because it usually reduces assembly costs, but because it has a far greater impact on the total manufacturing costs of the product. However to judge the effects of DFA at the early stages of the design, methods of early estimation of parts costs needs to be available in the design team.

Boothroyd and Dewhurst (2005), give a simple, clear example of how DFA is applied to a design and how a product starts out easy to design but difficult to assemble. The engineer focuses on reducing parts, integrating parts, and simplifying assembly. The end result is a more sophisticated design that is much easier to assemble. The cost is reduced by 42% and the assembly time is cut by 58%. In their research they have analysed hundreds of companies, discussed below, that have implemented DFM and case studies reveal, an average 42% reduction in labour costs, a 54% reduction in parts, a 60% reduction in assembly time , a 45% reduction in product development cycles, and a 50% reduction in overall costs. Figure 2.12, gives a good example of this:

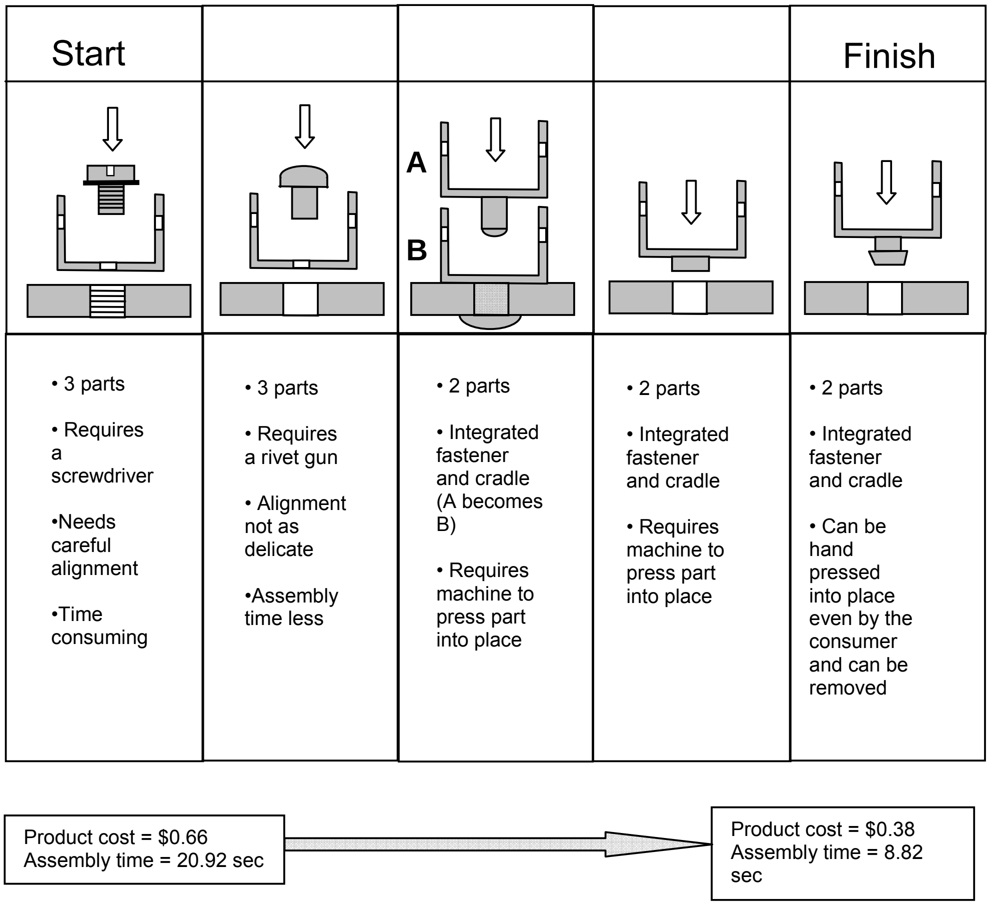

Figure 2.12 – DFMA Design Improvement Example, Boothroyd and Dewhurst (2005),

Boothroyd and Dewhurst (2005) in their white paper look a various leading companies throughout the world and discuss how DFM has affected their business and the design product. Hundreds of companies use DFM; some of the leading ones are; BMW, Boeing, Bosh, Ford, General Motors, Harley-Davidson, Honeywell, Lockheed Martin, Mercedes Benz, Rolls Royce, Volkswagen, Volvo … to name but a few. Boothroyd and Dewhurst discus various cases studies undertaken and the results from these.

Dell Computers is one of the leading computer manufactures. After undertaking a DFM program they managed to reduce assembly time by 40%, depending on the configuration of the PC. The three different chassis designs now use common metal and plastic parts, reducing inventory and tooling expenses. Assembly and training was standardised for the three types of computers in the program and the overall service time was reduced 20 to 30%

Boeing, one of the largest aircraft manufactures, reduced the number of parts on the F/A-18 C/D military aircraft, systems by 84%, reduced part cost by 73%, weight by 11% and assembly time by 89%

Whirpool used DFM on its most popular microwave oven. Their results included a 29% reduction in parts, from 150 to 106, a 26% decrease in assembly time and standardised cabling across product lines.

Boothroyd and Dewhurst (2005), state that there are two ways to engineer and manufacture a product;

- The "*over the fence*" method

In this case, the company engineers design a product and then throw it "*over the fence*" to the manufacturing team. The result of this is quite clear, although this seems extreme, in the authors twenty two years of working in a design and manufacturing environment this approach is found in design teams. If the product is not as easy to manufacture as it should be it will leave manufacturing engineers requesting changes by the design team. This may happen a number of times until the part can satisfy requirements. However during this unnecessary interaction the company is unable to satisfy demand for the product, leaving precious market share and windows opportunity missed, crucial for a company's survival in the market place

- The cross-functional method.

In this environment, product development engineers and manufacturing engineers work together from the start on the product design, using DFM techniques to explore and evaluate the design. The results from this will be clearly seen as a benefit to the company.

Herrera (1997) in this case study of implementing DFM and DFA on the development of the Longbow Apache helicopter discusses the benefits and improvements on the product after adopting these techniques: the results on the instrumentation panel were:

	Present design	DFM implementation on the design
Parts count	74 pieces	9 pieces
Fabrication time	305 hours	20 hours
Assembly time	149/153 hours	8/153 Hours
Total time	697 hours	181 hours
Weight	3 Kilograms	2.74 Kilograms
Cost	74 % reduction	

Fabricuis (1994) introduce a structured DFM procedure in order to facilitate the DFM process. After undertaking a number of pilot projects he showed that it is almost always possible to improve the manufacturability of products by following this seven step DFM procedure. During implementation of the structured approach 25-30% of manufacturing costs where saved without compromising on the product quality. Below is a brief outline of the process:

1. DFM Measurement

   Determination of the manufacturability of the present design and comparison with similar products on the market
2. Objectives

   Setting objectives for the manufacturability of the future DFM product
3. Main Functions

   Clarification of the various main functions of the product and interaction
4. Evaluation parameters and design ideas

   Clarification of the evaluation parameters and design ideas for each main function, and for key areas; corporate, family structure and component level
5. Generation of conceptual designs

   The generation of an alternative conceptual design, by determining product characteristics.
6. Verification and selection

   Measuring the manufacturability of the proposed conceptual design and comparing with the DFM objectives. Selecting the overall best conceptual design
7. Detail design

   Producing a design for the detail product, in accordance with the full potential of the chosen conceptual design.

2.5.1.1 Boothroyd and Dewhurst DFM Software

It was discussed in previous sections that DFM plays a major role in the design of a project in ensuring that the design is robust, the problems in achieving this in today's industrial environment have been highlighted. Boothroyd and Dewhurst have looked at the 'HOW' with the introduction of their DFM and DFA software.

Boothroyd and Dewhurst (2006a), introduce a new software tool for DFM allowing the development of estimates of the cost to manufacture, giving:

- A highly accurate cost-estimator.
- An aid to concurrent engineering.
- A useful design tool.
- An effective Vendor negotiating aid.
- A competitive Benchmarking tool.

Their DFM tool estimates the cost of products in the design from key product information: part name, life volume, overall envelope shape, part dimensions, material and manufacturing process. The software guides the engineer by indicating which materials and processes are compatible. Once these selections have been made the tool estimates an approximate cost estimate for producing the part and during this time the key product information is updated e.g. part volume, average machine rate, tolerance and number of cavities. This gives a step by step manufacturing process, so that cost can be identified through the manufacturing process. A final cost reduction summary identifies significant cost contributions that can serve as a focus to redesigning the part.

Along with the previous software Boothroyd and Dewhurst (2006b) introduce DFA software where they describe their tool as a software package that evaluates part design and the overall design of an assembly, it is a quantifiable way of identifying unnecessary parts in an assemble determining the assembly times and costs. Its main features are;

- Estimation of difficulty of assembly.
- Support design decision making.
- Benchmark existing products.
- Add focus to design reviews.
- Sharpen design skills.
- Integrate design and manufacturing.

The DFA software, prompts the engineer to think systematically about every part in the assembly. The key areas of the assembly design are entered into the tool including name and part number, to identify the product, Special handling operations are also defined along with securing methods and part envelope dimensions. This builds a bill of material which can also be loaded into the tool from computer aided design (CAD) models. Part manufacturing costs can also be added into the tool. To determine the theoretical minimum number of parts for the product, the engineer has to decide whether each item in the assembly must be separate from others. Once the DFA analysis has been completed reports and graphs are produced to aid the selection of the most efficient design form in the assembly, or further refinements can be made.

These two tools can be combined to aid the design to produce a manufacturable product with full implementation of DFM.

There are many other areas that use the 'design for', these are commonly know as design for X (DFX). Kuo (2001) reviews the many options that are available in the DFX field, as well as DFM & DFA there are many other derivatives of this. Design for disassembly and design for recyclability are recent developments; these have developed in many product designs simple due to the increase in the amount of discarded products. Disassembly in product design is important in order to make recycling economically viable in reprocessing technology. Disassembly is defined by Brennan et al (1994) *“the process of systematic removal of desirable constitute parts from an assembly while ensuring that there is no impairment of the parts due to the process*”

Design for environment (DFE), this is *“the systematic consideration, during new production and process development, of design issues associated with environment safety and health over the full product life-cycle”* Fiksel and Wapman (1994). The scope of DFE encompasses many disciplines when designing a product, including environmental risk management, product safety, occupational health and safety, pollution prevention, ecology, resource conservation, accident prevention and waste management.

Design for quality, DFQ, by its direct name is ensuring the product is designed to ensure quality, as discussed previously quality tools can only improve the amount of defects by 20%, the only reliable way to ensure a robust design is to design the manufacturing issues out of the product. According to Crow (1983), the objectives of DFQ are: design of the product to meet customer requirements, design of a robust product that can counter or minimize the effects of potential variation in manufacture of the product, continuously improve product reliability, performance and technology.

Design for maintainability (DFMt), Kapur and Lamberson (1977) define this as “the probability that a failed system can be repaired at a specific interval of downtime". This is to assure that the product can be maintained throughout its useful life-cycle at reasonable expense without any difficulty. This is particularity important within an industry such as aircraft manufacture, where it may be a customer requirement that to ensure that a specific part can be maintained in a allotted time, ensuring that the time the aircraft is on the ground is limited.

Design for reliability, Kuo (2001) looks at four factors; probability, specified functions, designated environment and length of time. It looks at how the designed product performs with in a specific environment and calculates its potential failure rate. There are three methods of calculating the reliability of a design:

- Equal allocation
- AGREE allocation
- ARINC allocation

Kuo (2001) discusses these techniques in more detail.

2.5.2 Design for Six Sigma

Six sigma was first introduced by Motorola (Pyzdek, 2003), in the mid- 1980's where Bob Galvin, Motorola's CEO at the time, started at the company on the quality path known as Six Sigma and became a business icon largely as a result of what he achieved in quality at Motorola. Using Six Sigma Motorola became known as a quality leader and a profit leader. In 1988 this secret became pubic knowledge and the Six Sigma philosophy became a new quality initiative. Even though Motorola has been struggling the past few years, companies such as GE and AlliedSignal have taken up the Six Sigma banner and used it to lead themselves into new levels in their customer markets.

The six sigma process for achieving a robust design uses a variety of quality techniques. Hoehn (1995) discusses the six step process shown in figure 2.13, each step capturing various data through the design process to aid the end result of the design:

1. Defining the Requirements, this is establishing the customer requirements both physical and functional.
2. This step is to identify the key characteristics that will potentially affect the end result of the product. In this step an analysis is required to identify these critical areas that will effect the customer's functional requirements.
3. Once these features have been identified it needs to be established as to whether each characteristic is controlled by parts, process or a combination of both.
4. The key features identify needs to be looked at in more detail to establish targets and tolerances breaking down each process into more detail.
5. The variations in these features are looked at and identified using various tools, statistical process control, design of experiments along with other suitable techniques.
6. The step combines the information gathered above to implement continuous improvement into the product and design.

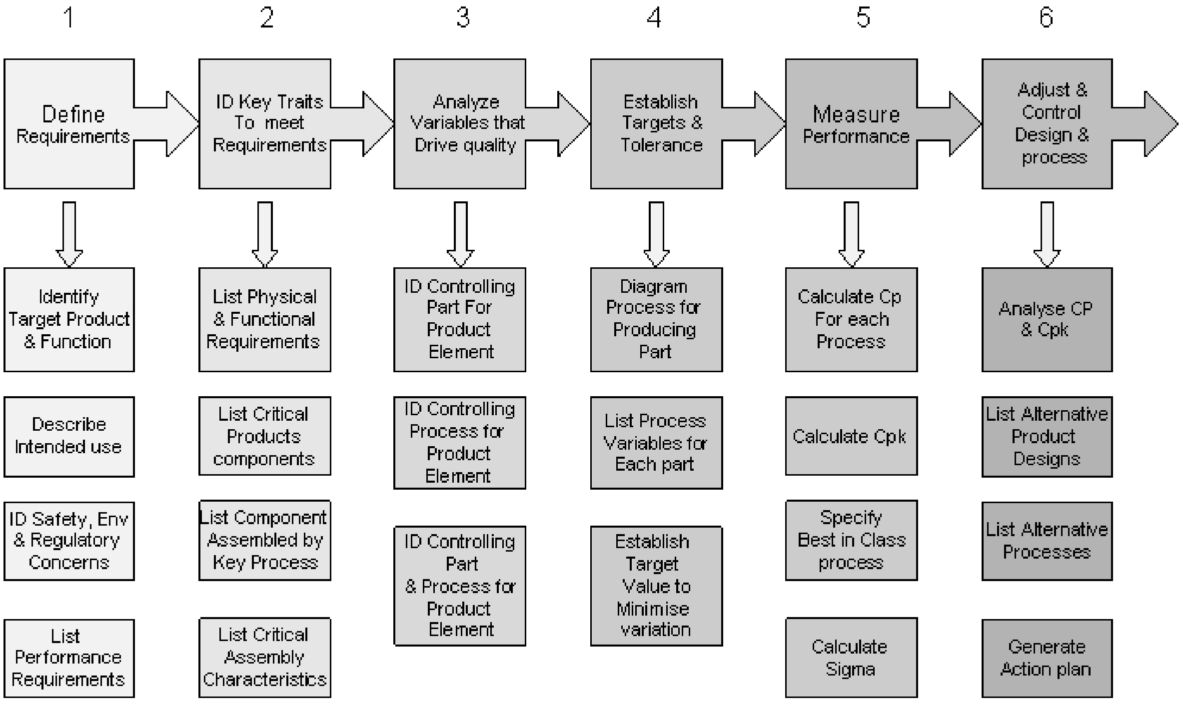

Figure 2.13 – Six Steps to Six Sigma, Hoehn (1995)

The aim of design for six sigma (DFSS) is to reduce the amount of defects that the designed products may produce in manufacture. This variation may be derived using various quality measures including Cp, Cpk (process capability indices), defects per unit (DPU), defects per million opportunities (DPMO) and sigma value. A defect is where a manufactured product is outside of its specified designed limits, making the product unable to meet its functional requirements. Hoehn (1995) classifies defects into:

1. Defects that are attributable to manufacturing process itself
2. Defects that occur in manufacturing, but are attributable to product design

3. Defects that occur at an integration level, but would not have occurred if adequate tests had been performed at lower levels
4. Defects that result in the product not fulfilling its requirements

The objective of DFSS is to remove the sensitivity of the design process prior to the start of manufacturing. Effort in the reduction of this should be focused on design and manufacture process decisions that have an impact on the customer's requirements. Hoehn (1995) claims that there are three possibilities for this to achieve a robust design

1. If the design has insensitivities but the process has a high degree of variability, then efforts should be focused on refining or changing the manufacturing process to minimise process variability.
2. If the design is highly sensitive but the process has low variability, the efforts should be focused on redesigning the product.
3. If the product has a degree of sensitivity and the process has a high degree of variability, then both the product and process must be corrected.

The term sigma refers to a standard deviation, this is a measurement of variation around the mean, figure 2.14 illustrates this.

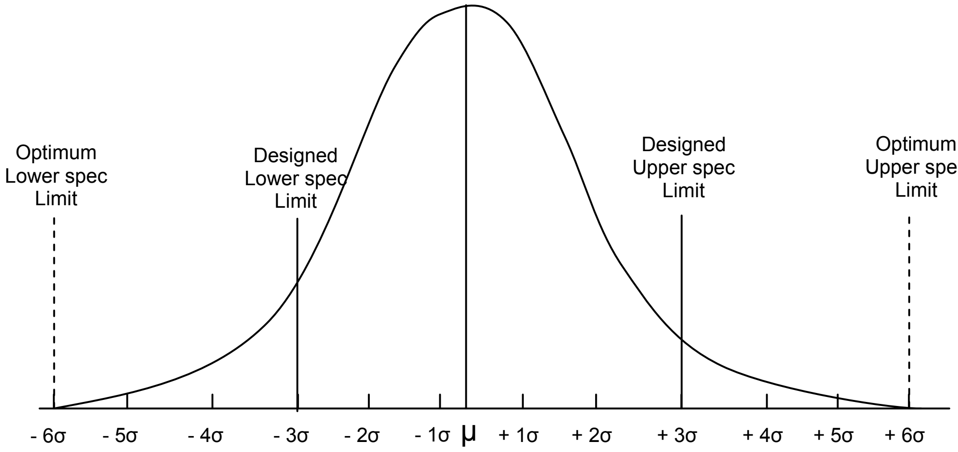

Figure 2.14 – Normal Distribution, 3 sigma design, 6 sigma optimum design

If the designed specification is within 3 sigma then, traditionally the amount of variation would have been an acceptable amount of variation for manufacture. However due to the introduction of DFSS, these traditional amounts of variation have been challenged to produce a 6 sigma variation. The benefits of these can be seen more clearly with the introduction of DPMO, defined by Motorola, (Harry, 1997) where they translated the sigma level into the number of defect parts per million parts manufactured, figure 2.15.

Sigma level	% Variation	DPMO, short term	DPMO, long term
+/- 1σ	68.26	317,400	697,700
+/- 2σ	95.46	45,400	308,733
+/- 3σ	99.73	2,700	66,803
+/- 4σ	99.9937	63	6,200
+/- 5σ	99.999943	0.57	233
+/- 6σ	99.999998	0.002	3.4

Figure 2.15 – Sigma Levels Translated to % Variation and DPMO

The benefits between the design specification and the optimum specification can be clearly seen, a simple practical example can highlight this. If three components were housed in an assemble fixture, figure 2.16, the middle component 'A' needs to be positioned during the assembly process between components 'B' and 'C'. The product's variation was designed to a specification of 3σ then component 'A' would fit 99.73% of the time. However, if the produces variation were increased to the optimum design specification of 6σ, then component 'A' would fit 99.999998% of the time.

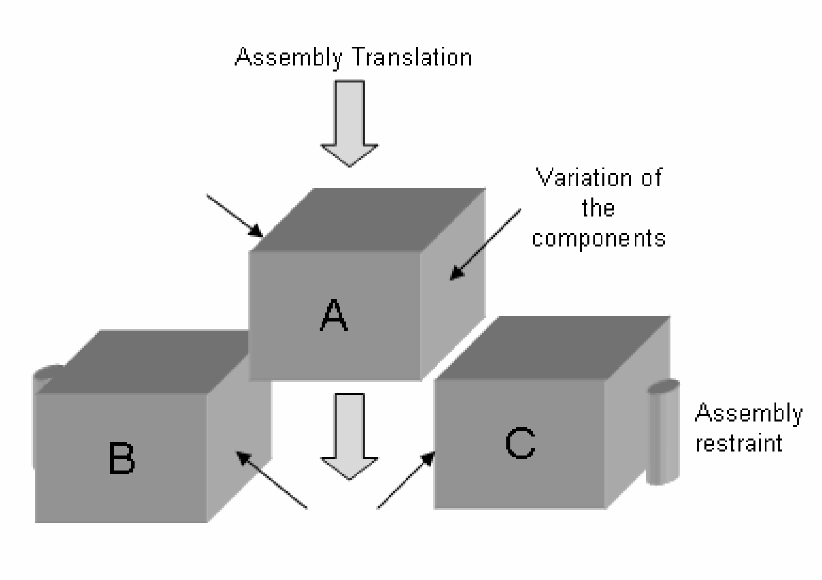

Figure 2.16 – Simple Assembly Example

Figure 2.15 above, shows 2 DPMO relationships; short term and long term this difference is explained in Koch (2002). If a component is being manufactured on a lathe, over time the cutting tool will wear, this will cause disruption of the performance variation to shift, while the designed specification limits remain the same. This shift was observed by Motorola and other companies that adopted this process. It was estimated that the shift would be around 1.5σ, and was used to define long sigma as apposed to short sigma.

2.5.3 Quality functional deployment (QFD)

One of the critical issues necessary to achieve a robust design is the setting of a clear and unambiguous requirements definition as discussed previously, where the design team capture what the customer requires of the designed and final manufactured product.

Quality functional deployment (QFD) produces a structured approach to the attainment of requirements definition, ensuring that the needs of the customer are considered. It provides a formalised method of linking the customer requirements to engineering, manufacturing and process decisions that companies need to make. According to Hauser and Clausing (1998), QFD originated in Mitsubishi's Kobi shipyard in Japan in 1975, this was adopted and developed by Toyota, who eventually made all of their suppliers use it to control product quality. The purpose of QFD has three main functions; first it helps the design team to identify the engineering characteristics under its control that might enable it to change customer valued attributes for the better. Secondly, it informs the design team about the possible detrimental effects on some customer-valued attributes of making improvements to others. Thirdly, it evaluates the product's performance in relation to the competitor's product

2.5.3.1 House of Quality (HOQ)

The HOQ is an integral part of QFD, it is a complex matrix that can be decomposed to matrices attached to each other, see figure 2.17. The use of the HOQ can be broken down into four areas:

- The customers needs

This stage is to identify what are the customers needs, what does the customer expect from the product when it has been designed and is introduced to the market. There are a number of methods that can be used to identify these, customer interviews and market research for example.

- Planning matrix

This is high-level product goal setting based on the market research data. This compares the company's business priorities with the customer needs.

- Technical responses

These are a set of product or process requirements, stated in the organisation's language, these are more commonly known as corporate expectations to distinguish them from the customer expectations.

- Relationship Matrix

This is the largest section of the HOQ. For each cell in the relationship section, a value is entered that reflects the extent to which the quality characteristic contributes to meeting the customer needs. This value along with the prioritisation of the customer needs establishes the contribution of the substitute quality characteristic to the overall customer satisfaction.

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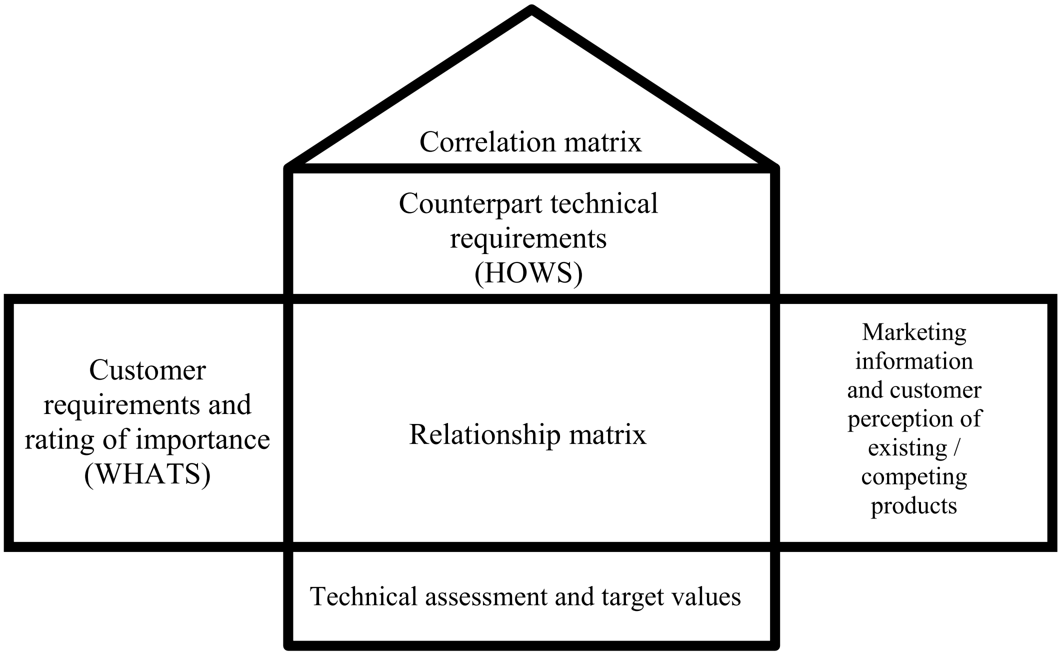

Figure 2.17 – The QFD House of Quality

This structured method relies upon a system of interlinked charts. The first chart relates the customer needs to the engineering characteristics that are under the control of the design team. The second chart relates the engineering characteristics to parts characteristics, it continues in this manner further down into the product life-cycle to look at issues around machine setting, staff training etc. These lower level decisions in the cycle can be linked through the higher level customer needs ensuring that with each decision the customer needs are considered. However, in practice few companies go down to this level of detail due to the design team's time and the effect it may have on the span times of the design life-cycle, delaying the delivery of the product into the market. The tendency is to stop at the first and second charts; Figure 2.18 is a simple diagram which shows how these interactions work in an organisation. It generally starts with the house of quality (HOQ), the customer "*whats*" are placed on the left of the matrix. This denotes the voice of the customer or, in other words, what the customer requires of the product. The QFD process prioritises these "*whats*" by making a series of judgments based on market research data. Then the "*hows*" are given at the bottom of the main matrix. The "*hows*" indicate how the design will technically meet the "*whats*". These *"hows"* are then prioritised to the right of the main matrix by being given a weighting.

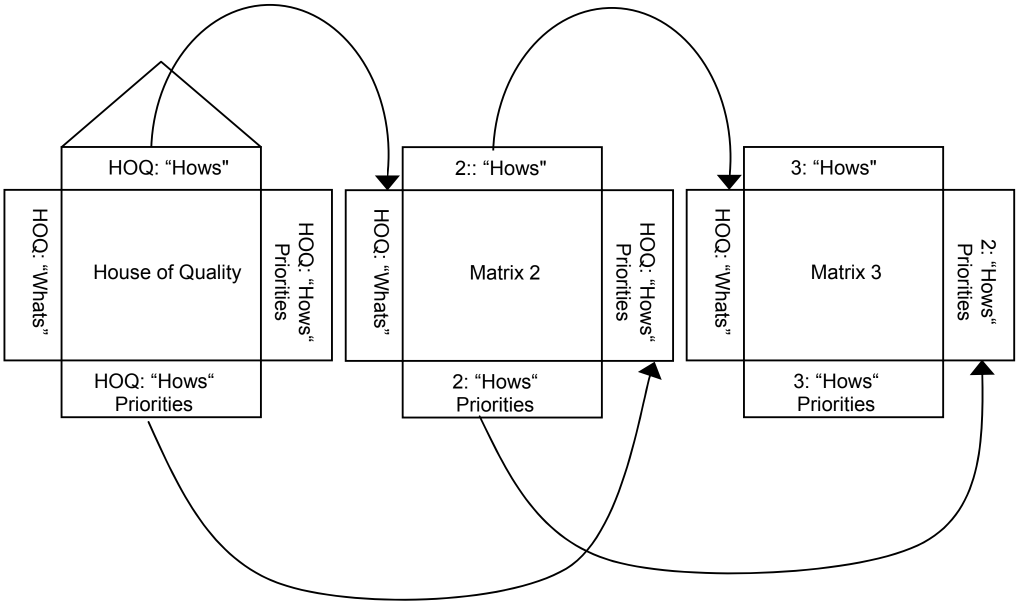

Figure 2.18 – Interrelated Matrices,Cohen (1998)

2.5.3.2 Why should an organisation use QFD?

To answer this questions (Cohen, 1998) looks at a number of areas in which an organisation can benefit in using this tool.

- Decreasing costs

Decreasing costs can be achieved by such actions as lowering the cost of purchase materials or services and reducing overhead costs in the product's lifecycle. QFD contributes to this in a number of ways; increasing the likelihood that a product or process design will not have to be changed or re-engineered and focusing the product and process development on the work that matters most to the customer.

- Increasing Revenues

QFD contributes to this by helping organisations to concentrate their efforts on customer needs, and translating these accurately into the product.

- Cycle time reduction

QFD is an important tool, in the reduction in cycle time during the design and development of a product. It helps develop the team's key decisions early in the development process, at the time when the cost of a decision is relatively low.

- Removal of the Obstacles to Rapid Product Development

One of the keys to competitiveness in the markets place is the ability to respond to the competition. Some of the obstacles can be removed by using QFD;

    - Poor understanding of the customer needs
    - Failure to strategically prioritise efforts
    - Willingness to take unmanageable risks
    - Tendency toward un build able designs, undeliverable services
    - Over reliance on formal specifications
    - Testing scenarios that fail to find the key defects

2.5.4 Discussion

As well as the design process in this chapter, the literature review has introduced how manufacturing and quality initiatives are critical to the completed product and how these should to be introduced into the design of the product. The QFD tool is a potential upfront process to introduce the design team to what are the essential requirements of the customer. Once these have been established it should give both structure and clarity to the design life-cycle.

The DFM approach, introduces the design team to knowledge of the impact the design may have in manufacturing with the aim of introducing these into the design and ensuring a smooth manufacturing phase in the product life-cycle. However, as discussed previously there are many areas that can be introduced into the design such as, design for assembly, design for the environment, design for disassembly, design for reliability etc. The question is "*Which of these should be incorporated in the design method?"* If we look at these theories, in-terms of aircraft production, there are many hundreds or thousands of components, as highlighted earlier in this chapter. Indeed if one looks at each area independently they clearly highlight that they will produce extensive savings in the product life-cycle. Which one should be implemented or should they all be introduced to the design method? This is why there is reluctance by the design organisation to introduce these due to the increase of the overall design life-cycle.

In over twenty years experience in the design and manufacturing areas of aircraft , a large amount of which has been working with integrated product teams in design for manufacture, the author has noted a clear reluctance to adopt these approaches into the design method. The manufacturing engineer has little control in overcoming these issues in a highly complex technical environment where the main drivers are to produce a product that is light in weight, structurally strong, with effective aerodynamics etc. Hence there still tends to be an "*over the wall*" culture within this environment, with valid reasons to do so from each engineering discipline involved.

The importance of the product being entered into the market place, as soon as possible, is highlighted by a comparison between Airbus's A350 and Boeing's 787 Dreamliner where it is crucial the products meet the market place at the scheduled time to gain advantage over the competitor. Figure 2.19 below shows how Boeing is losing its stake in the aircraft industry to Airbus prior to holding the competitive advantage for a number of years.

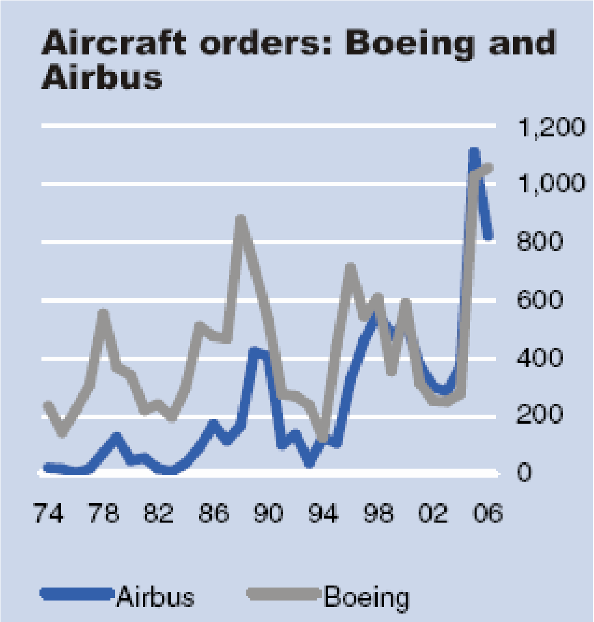

Figure 2.19 – Aircraft Orders, Boeing and Airbus, Heymann (2007)

However, decisions have to be made by the organisation as a whole, rather than in the enclosed environment of engineering and this has been one of Airbus' key areas of weakness, illustrated in the development of the A380.

Six Sigma introduces the idea of controlling the design using quality tools and implementing them into the design, industrialists are again questioning the impact to the overall life-cycle. The Six Sigma theory introduces cost savings into the design by controlling the amount of variation in the products, however if this is introduced into the aircraft industry it will have a bearing on one of the key customer drivers, weight. The simple example in figure 2.20 highlights this.

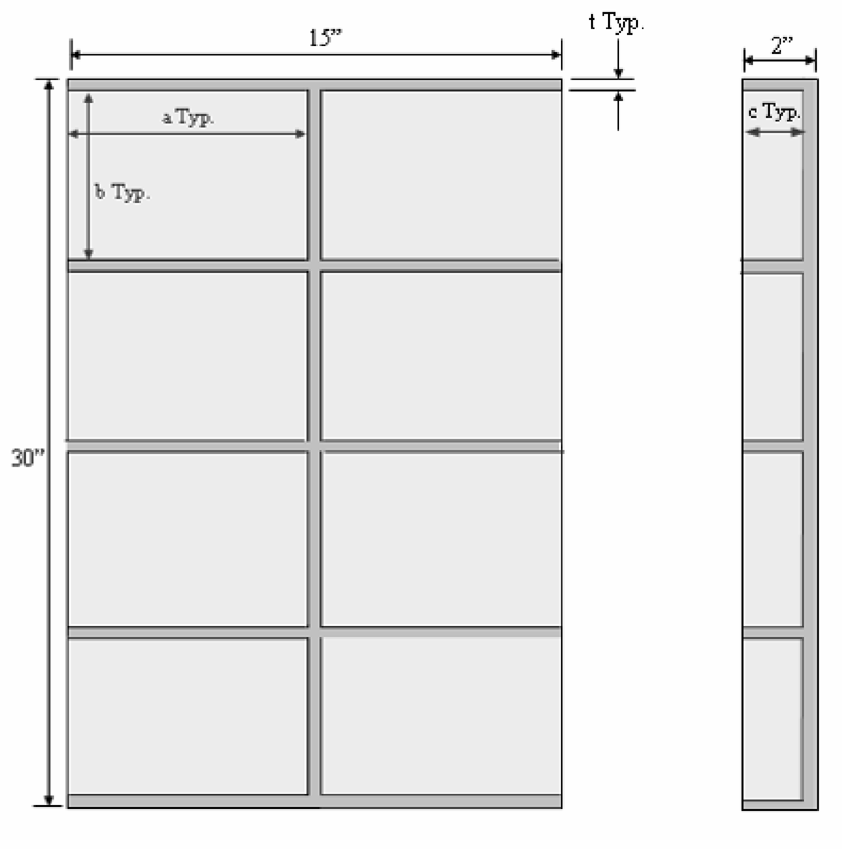

Figure 2.20 – An Aircraft's Simplified Keel Panel

The author has used the example in figure 2.20 to highlight the impact on an aircraft. He has assumed the following during the analysis:

All stiffeners and web sections have been produced at 0.1" nominal thickness

There is one vertical and three horizontal stiffeners

The outside dimensions are produced at nominal sizes

The manufacturing tolerance applied to the flange, web and stiffener thickness is +/- 0.007”

The author has assumed the density (p) for Aluminium is 0.103 lb/in^3, for Steel p = 0.284 lb/in^3, for Titanium p = 0.164 lb/in^3 and for carbon p = 0.058 lb/in^3

If the component is manufactured to its nominal tolerance (t), then the following case would apply

Case 1, t = 0.1

a=7.452”

b=7.375”

c=1.9”

Therefore:

Volume = (30 x 15 x 2)-8(7.45 x 7.375 x 1.9)

= 64.855 in^3

Mass if Aluminium = 64.855 x 0.103

= 6.680 lbs

Mass if Titanium = 64.855 x 0.164

= 10.636 lbs

Mass if Steel = 64.855 x 0.284

= 18.418 lbs

Mass if Carbon Fibre = 64.855 x 0.058

= 3.761 lbs

If the component was manufactured on its maximum tolerance (t) the effect on the weight is calculated below.

Case 2, t = 0.107

a=7.4465”

b=7.36625”

c=1.893”

Therefore:

Volume = (30 x 15 x 2) - 8(7.4465x 7.36625 x 1.893)

= 69.309 in^3

Mass if Aluminium = 69.309 x 0.103

= 7.139 lbs

Mass if Titanium = 69.309 x 0.164

= 11.367 lbs

Mass if Steel = 69.309 x 0.284

= 19.684 lbs

Mass if Carbon Fibre = 69.309 x 0.058

= 4.02 lbs

The percentage increase in mass from Case 1 is 6.87%

If a Six Sigma study concluded that to meet an acceptable process capability limit the tolerance of the component would have to increase to +/- 0.014”, the effect on the components weight can been seen in the calculations of Case 3.

Case 3, t = 0.114

a=7.443”

b=7.3575”

c=1.886”

Therefore:

Volume = (30 x 15 x 2) - 8(7.443 x 7.3575 x 1.886)

= 73.735 in^3

Mass if Aluminium = 73.735 x 0.103

= 7.597 lbs

Mass if Titanium = 73.735 x 0.164

= 12.093 lbs

Mass if Steel = 73.735 x 0.284

= 20.941 lbs

Mass if Carbon Fibre = 73.735 x 0.058

= 4.277 lbs

The percentage increase in mass from case 1 is 13.69%

The author highlights that these increases in weight would be greater if the components where more complex or the number of parts where increased. This is due to the increase in the number of potential tolerances.

If we translate these figures into one of the current military aircraft that is in manufacture, F/A-18C/D, it highlights the results if the increase of variation is introduced to create a Six Sigma product. Information gathered from Quilter (2007) can be introduced to the component in figure 2.20.

The airframe is built from approximately 49% aluminium, 15% steel, 13% Titanium, 10% Carbon Epoxy materials and 13% of other materials. F/A-18C/D has an empty weight only about 66% of legacy aircraft such as the F4 Phantom II, while being more capable in almost all regards. The more advanced construction techniques also reduce the parts count of the airframe. F/A-18C/D empty weight is 24,700 pounds, (Wikipedia, 2007).

If a Six Sigma study was conducted and to achieve an optimum process capability, it was decided that the design tolerance would have to be increased from +/- 0.007” to +/- 0.014” the additional weight can be estimated from the previous calculations. The author has assumed a conservative weight increase, due to the tolerance changes, to be 5%. This can be broken down to approximate weights for each material type.

Aluminium: The weight of aluminium in the aircraft is 12103 lbs. With the increase in tolerance, these sections of the aircraft would increase in weight by 60.51 lbs.

Steel: The weight of steel in the aircraft is 3705 lbs. With the increase in tolerance, these sections of the aircraft would increase in weight by 18.52 lbs

Titanium: The weight of titanium in the aircraft is 3211 lbs. With the increase in tolerance, these sections of the aircraft would increase in weight by 16.055 lbs

Carbon Fibre: The weight of carbon fibre in the aircraft is 2470 lbs. With the increase in tolerance, these sections of the aircraft would increase in weight by 12.35 lbs

Other materials: The weight of other materials in the aircraft is 3211 lbs. With the increase in tolerance, these sections of the aircraft would increase in weight by 16.05 lbs

Using Weber (1994) factors for the F/A-18C/D, $50,000 for every pound of extra weight due to fuel costs, over the life of the aircraft, this would equate to approximately $6,175,250 per aircraft

There has been almost 1500 F/A-18 aircraft build, the prime users being United States Navy, United States Marine Corps, Royal Australian Air Force and

Spanish Air force, (Wikipedia, 2007). Comparing these figures to the Weber (1994) these potentially hidden costs to the customer could be extremely significant. The author's example highlights that a small increase in tolerances would have a significant effect on a major customer requirement.

The author notes that depending on the material composition of the aircraft the effect on this hidden cost is a function of the overall material breakdown for the aircraft. For example effect to the customer would be minimised for the Typhoon. Information gathered from Eurofighter Typhoon (2006) and Lake (1998) highlights that this aircraft is built of about 50% composite materials, with substantial use of titanium and lithium-aluminium alloys.

2.6 Conclusion

This chapter looks at the current academic research, in various areas during the design of a product, from its initial conception through to manufacture and its eventual sale. It reviews the current published work in current design life-cycles and the design environment they operate in. Design for manufacture is discussed along with the current software tools that help introduce this into the design. Design for Six Sigma is one of the more current theories on how to influence the product through the design, and the main areas of the current research are introduced here. It was highlighted during the literature search that customer requirements are a crucial part of the design life-cycle, therefore the technique of quality functional deployment has been introduced into this chapter.

The review of the design life-cycle models may strive for different outcomes, although there is one clear point made by them all and that is the importance to adopt a structured method when designing a product, primarily introduced by Pugh in his

Total Design Activity Model in Figure 2.1. One of the main areas where most of the current design life-cycle models fail is in the detail of controlling a complex product such as airframe. French discusses this in his work by highlighting that there are many interactions and complex communications in this process with different levels of the life-cycle and disciplines. Given these factors French introduces additional feedback loops, illustrated in figure 2.4. French (1998) also highlights an important factor of the design life-cycle; he claims that "*design life-cycles cannot replace the gift of a talented designer*". Boothroyd and Alting (1992), Life-Cycle Design Concept, shown in figure 2.5, do not use the same steps as Pugh and French as they look at the importance of design for manufacture, environment, disassembly etc. in the design. To achieve a design with these characteristics they highlight that technical solutions should be guided by criteria containing the main elements shown in the outer cycle in figure 2.5. Within the aircraft industry these issues will be increased due to the complexity of the produce. The life-cycle needs to be compressed into a short time scale and introduce DFM concepts to reduce costs, along with maintaining a structured process for the design.

One observation from this research is the lack of control when customer requirements are fed through the design process. This work aims to introduce these areas into a new novel approach to the design life-cycle of aircraft manufacture. It will emphasise how DFM can be structured and measured into the design ensuring a robust design, while keeping the emphasis on what the customer requirements are and how close the design is to these initial requirements.

In the design environment this research has clearly separated this from the design life-cycle. The environment encapsulates the design life-cycle and, depending on which environment is selected, to control the sequence of the design life-cycle steps.

DFM introduces the importance that it has on the product in terms of quality and cost. The many different areas of DFM were discussed, how these are deployed will depend on the context of the product and to some extent the customer requirements. Boothroyd and Dewhurst's introduction of DFM and DFA is introduced into the literature review. This research clearly highlights the importance of DFM in product design also introducing the complexities of this and how easy an *"over the wall"* culture can happen and the potential effects this has on the design.

Design for Six Sigma is discussed in detail and highlights the current research in this area, looking at how this can iteratively affect the design and increase the both profits and quality. However, during this research it becomes clear that there are very few critical reviews of Six Sigma in this area and in the discussion it introduces potential issues with this approach. It looks at aircraft manufacture and the effect it would have on weight, a key customer requirement for the industry, introducing examples and calculations of the effect of the introduction of this.

It became apparent during the literature review how important the customer requirements are to a product, and then ensuring that the design encompasses these to ensure the final product meets the customer expectations. This is where quality functional deployment was discussed in detail, highlighting how a structured approach is used to establish the customer requirements.

These various sections in the literature review have clearly separate sections in product design. What this research aims to do is introduce novel approaches and tools which enhance the DLC models found in current academic literature in the specific field of airframe design and manufacture. It shows from the literature review there are clear gaps within product design of airframe manufacture.

Chapter 3 Methodology

3.1 Introduction

Having discussed the literature about design life-cycles and how design for manufacture integrates with these, there are certain questions for which current academic research has not been able to provide answers. As well as the problems encountered in an aircraft design and manufacture environment, the thesis will discuss the ways in which those questions will be approached. The present chapter discusses the research methodology employed in the research

Research methods refer to the ways in which research studies are designed and the procedures by which data is analysed in order to best achieve the research objectives. The author has chosen the term from American Heritage Dictionary which best fits the author's interpretation of methodology, *"a theoretical analysis of the methods appropriate to a field of study or to the body of methods and principles particular to a branch of knowledge"*. Therefore, this chapter provides a plan for studying the situation, not a simple checklist to be followed.

The nature of the research problem and its objectives has been defined at the onset of the research project to ensure that appropriate selections of research methods are chosen to provide sufficient flexibility in the research methodology.

The purpose of this chapter is to discuss the choice of research methods which were employed in attempting to answer the research questions. The chapter attempts to justify the appropriateness of the selected methods and the way in which they contribute to the achievement of the research objectives.

The method employed is based on four key inputs to the research:

- Review of literature
- Review by industry experts

- Expert interviews
- Use of experimental phases

3.2 Literature Review

The literature review is the documentation of a comprehensive review of the published and unpublished work from secondary sources covering all aspects of the research topic. A literature review is usually the first step of a research project as it helps to focus the researcher and ensures that the area of investigation is novel on certain aspects of the topic that were found to be important to the published studies. A major benefit of the review is that it ensures the researchability of the author's topic before "*proper*" research commences.

A definition of a literature review;

"*The selection of available documents (both published and unpublished) on the topic, which contain information, ideas, data and evidence written from a particular standpoint to fulfil certain aims or express certain views on the nature of the topic and how it is to be investigated, and the effective evaluation of these documents in relation to the research being proposed*" (Hart, 2003)

The aim of the literature review is to ensure that no important variable is ignored that has in the past been found repeatedly to have had an impact on the problem. A survey of the literature not only helps the researcher to include all the relative variables in the research project, but it also facilitates the creative integration of information gathered from the various sources and gives a basic framework to proceed further with the investigation. A good literature survey thus provides the foundation for developing a comprehensive theoretical framework from which hypotheses can be developed for testing.

Hart summarises the benefits of good literature review by proposing questions that the review of literature can answer:

1. What are the key sources?
2. What are the key theories, concepts and ideas?
3. What are the epistemological and ontological grounds for the disciple?
4. What are the main questions and problems that have been addressed to date?
5. How is knowledge on the topic structured and organised?
6. What are the origins and definitions of the topic?
7. What are the political standpoints?
8. What are the major issues and debates about the topic?

Whereas research in any area would benefit from the above, a literature review within this research is seen as essential for the successful achievement of the research aims. In the current research project, it was necessary to undertake this review in order to form a systematic view of the current state of research in the area of design for manufacture, design life-cycles and the environments in which they operate. The more focused the study is in the literature review the more it will help the author to produce an informed conclusion. Therefore, an effective literature study will have the following important functions:

1) Set up the framework of the project;
2) Identify the gaps in the currently existing literature;
3) Update and enrich the author's understanding of the subject matter;
4) Provide a structured plan to the stages of the research which are going to be followed.

5) The chapter on literature review is absolutely necessary if the reader is unfamiliar with design for manufacture.

The process of conducting the literature review starts with identifying the various published and unpublished materials that are available in the area of interest and gaining access to them. The second step is gathering the relevant information and establishing the links between the different sources so that they can be combined in a consistent picture of the research area. The final step is writing up the literature review (Hart, 2003)

3.3 Review by Industry Experts

The literature review looked at the extensive academic work in design life-cycles, design environment and design for manufacture tools. Each of these areas was reviewed independently and consideration was given to how they interact to produce an outcome where the product meets the customer's requirements and also considers its manufacturability. As this is paramount to producing a quality product while controlling costs, the author highlighted this link to the industrial environment. With this in mind the author proposed a number of expert interviews to enhance the literature review. This stage was seen as essential to not only validate the tool development but to ensure that the tool was compatible with the requirements from the aerospace industry.

3.3.1 Expert Interviews

The interview is a conversation with a purpose, according to Robson (2002). One of the reasons why interviews are a very common approach used in research is that they appear to be a quite straightforward and non-problematic way of finding things out.

A commonly made distinction between the types of interview is based on the degree of structure or formality of the interview. At one extreme, we have the fully structured interview, with predetermined set questions and the responses recorded on a standardised schedule. The other end of the scale belongs to the unstructured (completely informal) interview, where the interviewer has a general idea of interest and concern, but lets the conversation develop within this area. In-between the two extremes lies the semi-structured interview, where the interviewer has worked out a set of questions in advance, but is free to modify their order based upon their perception of what seems most appropriate in the context of the conversation. The interviewer can change the way questions are worded, give explanations and leave out particular questions which seem inappropriate with a particular interviewee or include additional ones (Robson, 2002).

The types of questions that are usually used in interviews are commonly of following three types: closed, open and scale questions. Closed questions force the interviewee to choose from two or more fixed alternatives. Open questions offer no restriction on the content or manner of the reply other than on the subject area. Scale questions ask for a response in the form of degree of agreement or disagreement.

According to Robson (2002) open-ended questions have the advantage of being flexible, allowing the interviewer to make a truer assessment of what the respondent really believes. This advantage makes open-ended questions the preferred type of question in all kinds of interviews, especially those which are of an exploratory character.

With the above information taken into consideration, along with the author's experience in the industry, the preferred interviewing process should be more exploratory rather than descriptive. Therefore, an unstructured set of questions was seen to be more appropriate and useful for the purposes of the research than a structured interview. This would ensure an effective contribution from extremely experienced industrialists and would reinforce the research area. The author was aware that the interviewees were people with different backgrounds, expertise and areas of knowledge so the interviews remained relevant to the expertise of the interviewee. The author highlighted topic areas to stimulate a discussion; these were flexible enough to give the interviewee the freedom to express their views and ideas in all the aspects of design and manufacture of aircraft. Therefore it was not possible for the author to list the questions and answers from the interviews.

The interviews with senior industry specialists from manufacturing engineering, design engineering and structural engineering within the aircraft industry will build a comprehensive view of the research, the aim of the author being to get a detailed view of the issues and complexities that may occur in this area. These issues are not always discussed in academic literature and that is the reason for the interviews being unstructured as their aim was exploratory and not descriptive.

3.4 Use of Case Studies

Denscombe (2003) explains that "*the concept of case study captures an important aspect of the decisions we face in research. It highlights, in particular, the choices that we have to make about how many cases to investigate and how these are to be selected*". When researchers opt for a case study approach they buy into a set of related ideas and preferences which, when combined, give the approach its distinctive character, (Denscombe 2003)

Robson (2002) highlights that in many case studies it is appropriate to study more than a single case. The multiple cases may be attempts at replication of:

- An initial finding, conclusion, etc:
- They may build upon the first experiment, carrying the investigation into an area suggested by the first study.
- They may seek to complement the first study by focusing on an idea not originally covered.

Robson (2002) recommends how the case studying activity should be carried out; the first case study should provide evidence which supports some theory about what is going on. This theory, and its possible support or disconfirmation, guides the choice of subsequent cases in a multiple case study. Cases are used where either the theory would suggest that the same result is obtained, or that predictably different results will be obtained.

The main area of the research by the author is the design evaluation tool and how it measures the manufacturability of a design. With consideration of the above and with the environment in which the tool will operate the author has decided to use a tool development process to develop and validate the design evaluation tool, in three experimental phases.

Phase 1 – Validation of the Process on a Theoretical Study of an Aircraft Tail

The design evaluation tool uses a large amount of data and mathematical calculations to establish how manufacturable the design is. Due the complexity of these calculations and data, the tool was difficult to validate. To solve this problem the author designed, in detail, a product to verify the proposed design evaluation model. The design is based on a simplified version of an aircraft's vertical tail; it was designed in 3D to closely simulate an aircraft structure. This experimental phase was to provide the design evaluation tool with a typical product for analysis. The intention is to validate the approach adopted by the tool and so establish a valid base onto which further experimental phases can be built to establish the manufacturability of designs.

Phase 2 – Design Evaluation of an Aircraft Structure currently in Production.

Following a critical review of the output of experimental phase 1 by senior industrialists, a question was posed to the author "*could an evaluation of a design be undertaken for a proposed alternative design, comparing its manufacturability against an existing design?*" The industrialists recognised that until presented with the author's research there was no way to measure which design would produce less defect cost to the business. An alternative design had been proposed to replace a current product's design. The author was presented with preliminary data of the proposed design and asked to establish whether the proposed design should be developed further to replace the existing design. This was then developed into experimental phase 2.

Phase 3 – A Comparison between the Design Evaluation Tool and the Actual Results from Manufacturing an Aircraft Structure in Production.

To demonstrate the methodology the author proposed a third experimental phase. The aim of this phase is to evaluate the design of a product in current manufacture and analyse the results, comparing them with the actual defects that have been submitted by the manufacturing companies involved. The design evaluation tool produces an estimation of defects that may arise, validated in experimental phase 1. From this data a concession count can be estimated.

3.5 Development of Research Method

Chapter 1 introduced the research questions. To help resolve these complex research questions a number of research objectives have been introduced, as set out in chapter 1. These are set out below;

Objective 1

To review the literature to establish current general approaches to product design.

Objective 2

To review current approaches in the design life-cycle and design for manufacture in the design of low volume, high complex products. Review techniques that enable design for manufacture to be deployed into the design life-cycle

Objective 3

To develop a novel improved design life-cycle model that caters for the design of low volume and high complex products that emphasises adherence to customer requirements, controlling the design inputs to achieve the desired outputs.

Objective 4

To categorise the current design environments that the design life-cycle operates in, analysing their strengths and weaknesses and identifying which environment would benefit a low volume high complexity product during its design.

Objective 5

To produce a novel design for manufacture tool that can be used in the author's novel design life-cycle to access how decisions made during the design stage will affect the overall cost and quality of the product when in manufacture.

The diagram in Figure 3.1 shows how the research methods selected relate to specific objectives. The following sections of the current chapter will discuss the ways in which the research methods will help to achieve the objectives. The discussion will also cover the advantages and disadvantages of the chosen method, its relevance to the specific area of research, and the challenges which are expected to be faced in the employment of the methods.

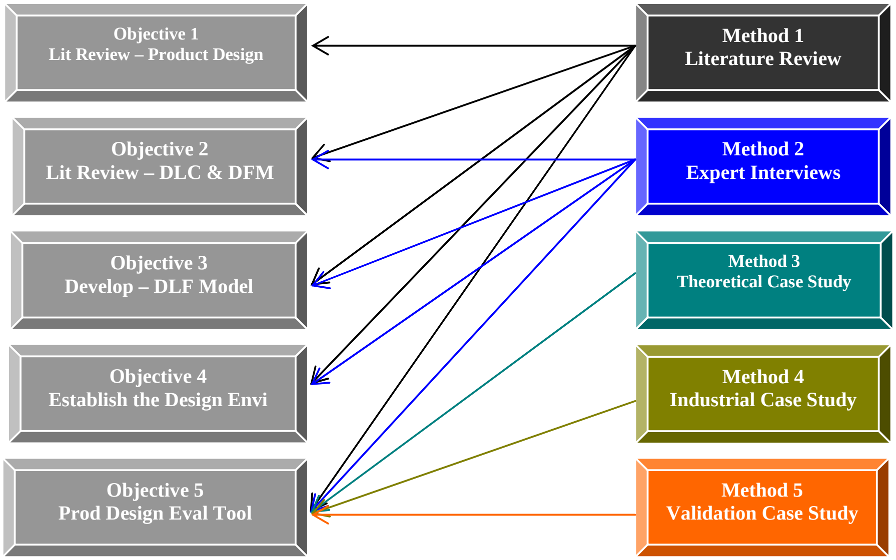

Figure 3.1 – Mapping of Research Methods against Objectives

Method 1

Conduct a literature review in the area of design for manufacture, design life-cycle, design environments and structured approaches to design.

The literature review which was undertaken at the first stage of the research, was necessary to provide the researcher with a broad overview of the area of the research. It aids the author to confirm the validity of the preliminary defined problems, to identify new problems helping to focus the research on the relevant issues and ensuring a contribution to knowledge is achieved.

Method 2

Expert interviews with industry specialists will be undertaken to review issues that are present in the industrial environment.

With the nature of the research the author will have access to industry experts in the field of aircraft design and manufacture. This will allow the author to conduct a number of relevant expert interviews to enable a comparison to be drawn between current academic research and the industrial issues identified. The author will use this combination to develop novel solutions and ensure that the research is aligned to the requirements of the aircraft industry.

Method 3

Undertake a theoretical experimental phase of the design evaluation tool.

This will validate the intention of the design for manufacture tool ensuring the outcome meets the researcher's objectives. A major section of aircraft structure will be designed with a 3D model produced by the author to ensure this experimental phase is a true representation of aircraft structure. The aim is to validate the mathematics of the design evaluation tool, ensuring the output can be used to establish the manufacturability of the product.

Method 4

Undertake a series of industrial experimental phases.

An industrial experimental phase is to be selected with help from industrial specialists. The product will be selected carefully ensuring it is complex enough to highlight the methodology around the design evaluation tool. A fully comprehensive statistical process control environment should be evident to provide the design evaluation tool with robust manufacturing data.

Method 5

Validation of the design evaluation tool, via an experiment phase.

The data output from the design evaluation tool will be compared with the defects submitted by the manufacturing organisation. From this, a comparison will be made between the design evaluation tool and actual industry submitted defects. Once the comparison has been undertaken the parameters of the design evaluation tool will be adjusted to ensure a more accurate analysis of future product is achieved.

The output from the five methods described above is to be summarised and discussed so that the conclusions from the study can provide inputs to the final stage of the research; the development of a design evaluation tool. This tool, as stated in the introduction to the research project, is the ultimate goal of the author.

3.6 Conclusion

The research methodology which has been discussed in this chapter is expected to provide a feasible way of achieving the research objectives. Overall, the author is confident that the initially designed methodological approach to the research was sufficiently well thought-out and well-structured to enable the research to come to a successful end by producing findings and conclusions which would strongly benefit the future development of design for manufacture in the aircraft industry, particular further development of the design evaluation tool. The methodology highlights the positive combination of academic knowledge linked with industrial knowledge through the many different disciplines in the design life-cycle of aircraft, this will ensure a positive conclusion to the questions and conclusions posed by the author.

Chapter 4 Background to the Problem

4.1 Introduction

In Chapter 2 the author undertook a literature review of current academic knowledge in three main areas: product design; design life-cycles, design environment / design for manufacture. The findings of this review were combined with the outcomes from expert interviews held which raised issues in the field of design and manufacture in the aircraft industry. This combination proved to be very successful for the author in providing the identification of current issues in the knowledge of design for manufacture and the identification of a number of key areas to which the author can contribute to existing knowledge.

4.2 Design Life-cycle in a High Complex low Volume Industry

In Chapter 2 the author introduced an in-depth review of various design life-cycles and highlighted a number of potential areas which could benefit from the introduction of a novel design life-cycle. It is critical to adopt a structured method when designing products such as aircraft, primarily due to the high number of complex components involved, however the author has established that current design models, although highlighting complexities in the design process, do not resolve many problems highlighted by experts in the aircraft industry. The importance of the engineer's experience has been discussed in Chapter 2 and in particular how it can benefit decision making in the design life-cycle.

Within the aircraft industry the range of design information is greater and more complex than most other industries due to the complexities of the product. To highlight this, the reader is introduced to a typical decision process that an engineer may have to consider in the design of a product. This example was introduced to the author during discussions with industry based engineers.

The selection of fasteners for a component that is statically loaded in shear is a typical engineering problem faced by a structural engineer. To calculate this, the margin of safety must be determined. Put simply, this is the proportion of allowable load that the fastener can withstand.

1. The margin of safety (M.S) of the fastener has to be calculated as follows:

$$MS = \frac{Allowable\ Load}{Applied\ Load} - 1$$

The allowable load is the amount of load the fastener can withstand before destruction occurs; this is primarily dependent on the fastener diameter. The greater the diameter, generally, the higher the allowable load will be.

The applied load is the amount of load that will be applied to the fastener during flight. An example may assist the reader:

Allowable load = 2500 lb

Applied load = 2400 lb

$$MS = \frac{Allowable\ Load}{Applied\ Load} - 1$$

$$MS = \frac{2500}{2400} - 1$$

= 0.042

The fastener can withstand 4.2% more load before shear failure of the fastener will occur.

To achieve minimum weight, which is a major customer requirement in the aircraft industry, the margin of safety should be close to zero. The reason why the fastener margin of safety can be zero is that, in the aircraft industry there is already a margin of safety programmed into the finite element model. This introduces a factor into the load calculation to allow 50% more load to be carried by the structure.

Once the fastener safety margins have been calculated as acceptable i.e. not below zero, it has to be established whether the hole itself can withstand the applied load. This is referred to as the bearing allowable.

2. The bearing allowable calculation is:

$$Bearing\ M.S. = \frac{Material\ Bearing\ Allowable\ Stress}{Applied\ Bearing\ Stress} - 1$$

Where:

Material bearing allowable stress is dependent on the material type.

$$Applied\ Bearing\ Stress = \frac{The\ Force\ Applied}{Diameter\ of\ the\ hole \times Thickness\ of\ the\ Material}$$

Again, an example may assist the reader.

Material bearing allowable	= 200400 lb
Force applied	= 2400 lb
Diameter of the hole	= 0.250”

Thickness of material = 0.1”

Therefore:

$$Applied\ Bearing\ Stress = \frac{The\ Force\ Applied}{Diameter\ of\ the\ hole \times Thickness\ of\ the\ Material}$$

$$= \frac{2400}{0.250 \times 0.1}$$

= 96000 lb

$$Bearing\ M.S. = \frac{Material\ Bearing\ Allowable\ Stress}{Applied\ Bearing\ Stress} - 1$$

$$= \frac{200400}{96000} - 1$$

= 2.09 – 1

= 1.09

Therefore the hole could withstand 109% of the current load, and in this simple case, the fastener is more critical than the hole, due to the lower M.S.

The reader should bear in mind that the above example is only one minor feature of the aircraft’s structure. To complete a design many hundreds of thousands of decisions similar to this have to be undertaken.

Once the fastener size has been derived other engineering disciplines have to validate these results against their requirements and the customer requirements. A good example of this is the location of the fastener, as the assembly manufacturing engineers need to assess the accessibility for installation. This assessment may conclude that the fastener needs to be relocated. This would require the above calculation to be verified.

These complexities are exacerbated when design for manufacturability is introduced into the design. It is not merely satisfactory to control data as the current design life-cycle models highlight, it needs to be compressed into a short time scale to enable the introduction of design for manufacture concepts to reduce costs whilst with maintaining a structured process for the design.

In addition the author also discovered from the current research that there is an increasing lack of attention to the customer requirements in the design as it develops through the life-cycle.

From the literature review and expert interviews with industrialists in the design and manufacture of aircraft the author has highlighted a number of key findings that current research literature does not cover. These are highlighted below:

- A design life-cycle needs to be developed in order to manage the complexities of a design in the aircraft industry.
- In aircraft design, customer requirements need to control the activities in the design life-cycle at all stages.
- The design life-cycle needs to ensure that the knowledge of experienced designers is captured and maintained throughout the structured framework for the design.

4.3 Design Environment

During the literature review the author reviewed a number of design environments, as discussed in Chapter 2. The advantages and disadvantages of each environment can be clearly seen in the current literature.

The literature highlighted the importance of ensuring that the design operates in the correct environment for the product and the organisation. Many industrialists have little knowledge of these environments as they concentrate more on the design life-cycle itself. Many academics refer to the design environment as the *"design definition"*. The author, in Chapter 2 discusses the difference between the design life-cycle and the "*design definition*".

With the knowledge gained through the literature review the author has introduced a number of findings from both industrial and academic knowledge:

- Industrialists in the aircraft industry need to link the advantages and disadvantages from the design definition to help structure their design.
- Industrialists need to be able to select the most appropriate design environment to suit their organisation and product.

4.4 Integration of Design for Manufacture Analysis in the Design Life-Cycle.

One clear area that the combined review of literature and industry experts in the aircraft industry has highlighted is the introduction of design for manufacture within the design life-cycle. The benefits of this are highlighted in Chapter 2. After conducting a number of expert interviews the author realised that this topic was a complex issue when designing aircraft. Design teams are pressured by the organisation to produce cost effective designs that in turn will enhance the company's profits. Markets also increase pressure on design teams to ensure that the product is introduced to the market as early as possible to maintain a competitive advantage over rival companies.

The author's findings from the literature review and industrial observations highlight the following.

- A company needs to produce a quality, cost-effective product to enable a profit. This requires a design that is manufacturable.
- Design teams in the aircraft industry need to design products to customer requirements ensuring that the end result is a safe aircraft that meets these requirements.
- There is commercial pressure to introduce their product to the market place prior to the competitors.

To highlight this, the author uses the fastener example used previously in this chapter. The decision as to how strong a fastener should be to meet requirements is relatively straight-forward and can be selected by the introduction of calculations. Weights engineering can select the fastener in a similar manner. These decisions from engineering disciplines can be substantiated by tangible data. The manufacturing engineering discipline is under pressure to ensure that the design can be manufacturable, reducing "down stream" costs, without tangible data to support the decision.

Therefore, manufacturing has to deal with the outcomes of the design in production, this is referred to as an "over the wall" design. These finding from the literature review and expert interviews have introduced a number of issues to the author with respect to the present knowledge in this field.

- Manufacturing engineers are unable to measure how manufacturable the design is.
- Manufacturability data needs to be introduced into the design life-cycle without a major impact on the design life-cycle span time.
- The organisation requires information on the potential additional costs that may occur once manufacturing commences.

4.5 Conclusion

The author has reviewed knowledge from current literature and industry by expert interviews and, after closely studying both areas, gaps in current knowledge have been identified primarily in the field of design for manufacture. There are three main areas that are introduced by the author:

The design life-cycle in which the design is matured is critical to control the outcome of the design process. Current literature in this area highlights the importance of a structured approach to the design to control the many different variables. However, when designing large complex products such as aircraft it becomes more difficult to control such a large amount of complex information and their decision processes.

The design life-cycle operates in an environment sometimes referred to as the "*design definition*". The literature highlights the different types of design definition which is generally linked to the product type and the configuration of the organisation. From this the author has derived a number of key findings in this research area.

The third and most critical area to the research is the integration of design for manufacture within the design life-cycle enabling a reduction of potential defects in manufacturing. The literature review highlighted that design for manufacture plays an important part in the outcome of the design, and should be an integral part of the design. However, the problems that may occur when this is introduced into the design have not been discussed in Chapter 2. In some cases these problems introduce an "*over the wall*" mentality to design and manufacture, leaving the manufacturing engineers to deal with defects and problems as they occur. One of the main reasons for these issues is the unavailability of tangible analysis; e.g. a predicted cost to manufacture a product, which the manufacturing engineers can use to substantiate their reasons for a change to the design. The author's findings highlight a number of areas in which a contribution of knowledge can be made.

The findings from this chapter introduce the framework to the research and to the following chapter.

Chapter 5 Solution Selection and Development

5.1 Introduction

The present chapter reviews the conclusions drawn from the research described in Chapter 4. It will attempt to answer the research questions presented in Chapter 1. Section 5.2 introduces a tool that aids the selection of the design environment in which the design life-cycle will operate. In Section 5.3 the author introduces his novel design life-cycle that fills the gaps of existing design life-cycles, discussed in previous chapters. In Section 5.4 the author discusses the importance of key characteristics and design for manufacture in the design life-cycle, highlighting how these are introduced into the author's proposed design life-cycle. The main area of the research is introduced in Section 5.5 and discusses the development of a novel tool to analyse the design for its manufacturability early in the design life-cycle and prior to the onset of the manufacturing phase.

5.2 Selection of the Design environment model

As discussed in chapter 2, it is important for an organisation to decide on the environment in which the design life-cycle should evolve. The design environment is the global environment in which the design life-cycle operates and it structures the way the engineering activities are established and developed. As identified in the literature survey, Yazdani and Holmes (1999) identify four very different models for the design environment.

In selecting the most appropriate environment for the product, the different environments can be carefully analysed using a novel methodology to measure the major areas that relate to the design and manufacture of an aircraft. Each environment can be scored and analysed as to its appropriateness within the DLC.

The author, along with key discipline leads in the aerospace industry, selected four key parameters that would have the greatest importance to the DLC for aircraft design and manufacture, these were:

1. The effect the design environment has on the requirements definition
2. The effect the design environment would have on the overall cost.
3. The effect the design environment would have on the business, post design release.
4. The effect the design environment would have on the design life-cycle.

Each of these contains two sub parameters that will be scored; "*high*" indicating a beneficial positive effect, '*medium*' and "*low*" indicating a less positive effect these scores will achieve the overall weight for the specific design environment.

These criteria have been carefully selected to optimise the selection of the design environment in the aerospace industry. The author highlights the fact that if this was applied to a different design and manufacture industry other than aerospace, the author recommends that the criteria must be re-evaluated to suit the specific organisational needs. The author identifies this area as having potential for further work, where various organisations can identify set parameters that can be selected to evaluate the compatibility of the design environment for their situation.

The author presented four questions to various discipline leads from manufacturing engineering, design engineering and structural engineering working within the aircraft industry. He asked them to score each question in relationship to the four design environments, sequential model, design centred model, concurrent definition model and the dynamic model. The questions that were presented are listed below:

1. Effect on Requirements Definition

Would there be a positive / negative effect on the Requirements Definition if a specific environment was deployed for the design life-cycle to operate in?

a) Customer Requirements

Would it have a high, medium or low impact on the products customer requirements if the specific design environment was adopted?

b) Robust Design

Would the specific design environment be conducive to a robust design, high, medium or low impact?

2. Effect on the Overall Cost

Would there be a positive/ negative effect on the overall cost if a specific environment was deployed for the design life-cycle to operate in?

a) Control of Defects

Would it have a high, medium or low impact on controlling defects if the specific design environment was adopted?

b) Cost Effective Design

Would the specific design environment be conducive to a cost effective design high, medium or low impact?

3. Effect on Business Post Design Release

Would there be a positive / negative effect on the business post design release if a specific environment was deployed for the design life-cycle to operate in?

a) Manufacturable Design

Would the specific design environment be conducive to produce a manufacturable design; high, medium or low impact?

b) Help Control Business Decisions

Would it have a high, medium or low impact on helping to control the business decisions?

4. Effect on DLC

a) Would it help reduce the overall DLC

Would it have a high, medium or low impact on reducing the design life-cycle if the specific design environment was adopted?

b) Minimise Design Change

Would the specific design environment be conducive to reduce the amount of design change that occurs in the DLC; high, medium or low impact?

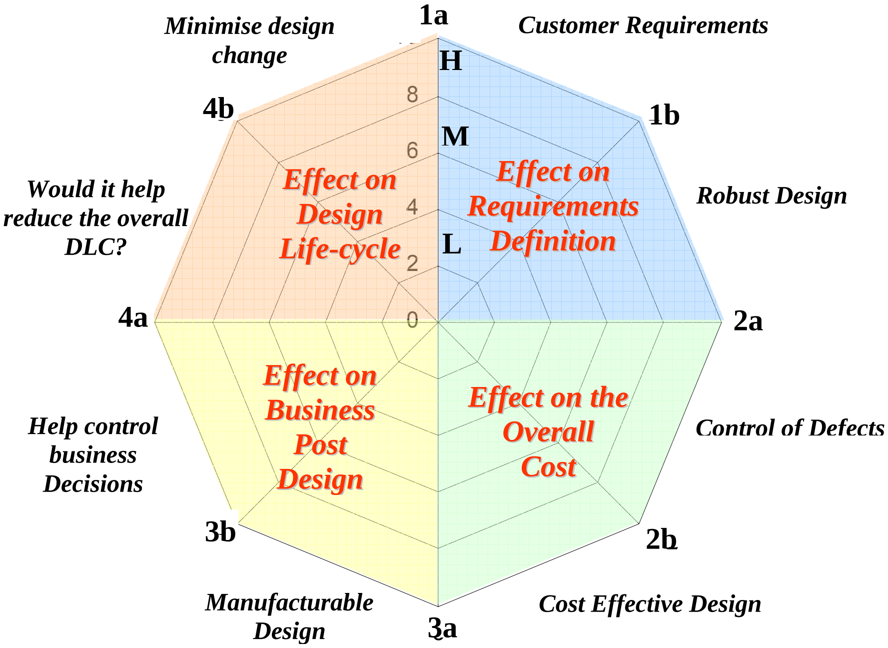

Figure 5.1 – Layout of the parameters for the environment evaluation

Figure 5.1 illustrates the layout of the parameters and forms a key to the results in figure 5.2 which shows an evaluation of each of the four design environments.

Each design environment has its strengths and weaknesses within the DLC; an evaluation was undertaken in the aerospace industry by experienced chief and lead engineers that have worked extensively in the four environments discussed previously. The results from the above questions are presented below, where the industrialists awarded the following points to the questions posed by the author, using the criteria of High = 10, Medium = 7 and Low = 3.

Sequential Model		
Question	***Result***	***Score***
1a	med	7
1b	low	3
2a	low	3
2b	med	7
3a	low	3
3b	low	3
4a	med	7
4b	low	3
Total	**36**	

Design Centered Model		
Question	***Result***	***Score***
1a	med	7
1b	med	7
2a	high	10
2b	med	7
3a	high	10
3b	high	3
4a	low	3
4b	med	7
Total	**54**	

Concurrent Definition		
Question	***Result***	***Score***
1a	high	10
1b	med	7
2a	med	7
2b	med	7
3a	high	10
3b	low	3
4a	med	7
4b	med	7
Total	**58**	

The Dynamic Model		
Question	***Result***	***Score***
1a	med	7
1b	med	7
2a	low	3
2b	med	7
3a	med	7
3b	med	3
4a	high	10
4b	low	3
Total	**47**	

This evaluation concluded that concurrent definition showed the highest level of strengths. To aid in the visual outputs from the proposed questions the author has produced radar graphs, figure 5.2. This clearly highlights the selection of both the strengths and weakness of each environment by the shaded area. The author used this graphical technique to present clear results back to the discipline leads involved in this assessment.

The strengths and weaknesses of a concurrent environment are discussed in detail in Section 2.4.3, however there are a number of areas that need to be considered when selecting such an environment, one of the most crucial being communication throughout the DLC between disciplines. Holmes 1994 and Haque 2003, discuss this in more detail. The design environment for the DLC has to be evaluated and selected carefully, the author highlights the possibility that a product may be too specialised for the current documented environments, and therefore further research in this area would be required to develop a hybrid environment.

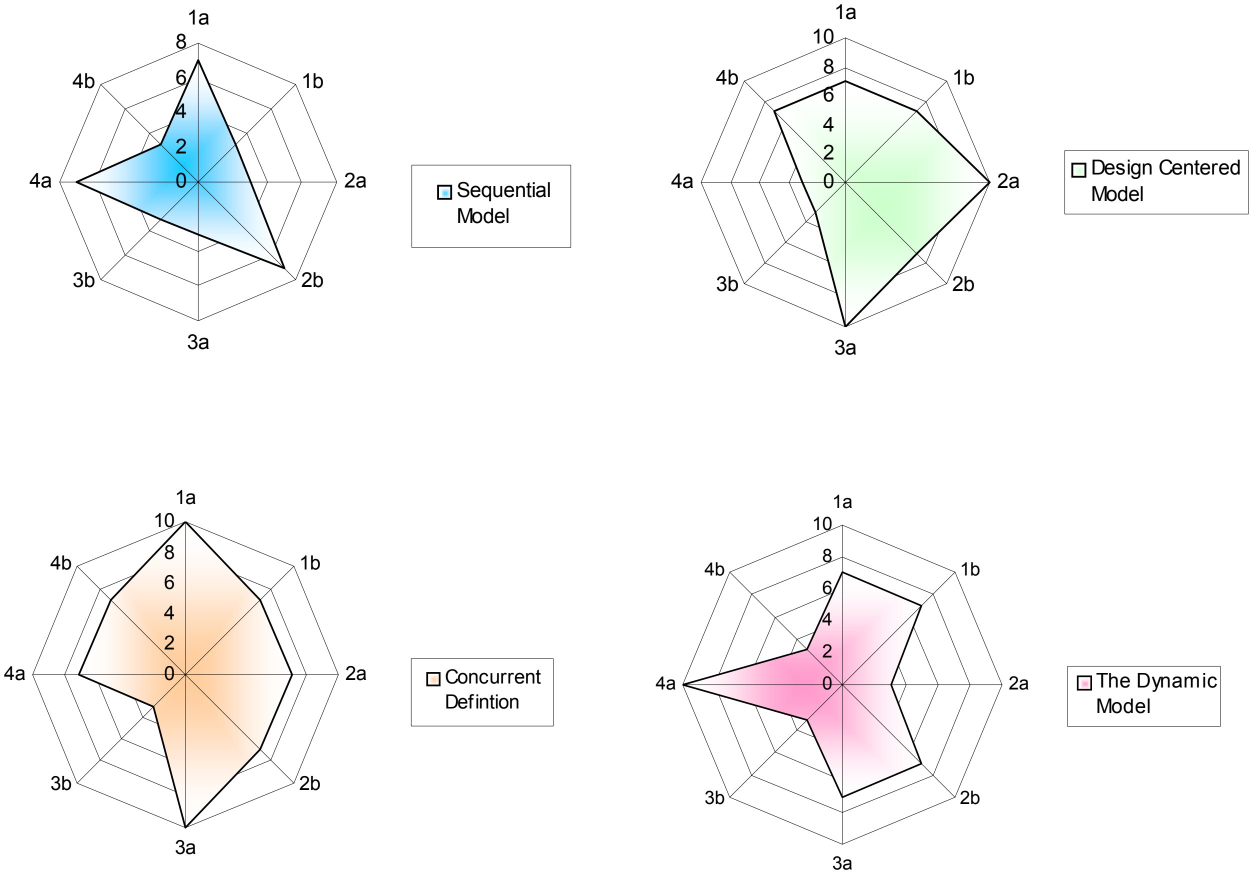

Figure 5.2 – Design Environment Evaluation

5.3 Selection of the Design Life-cycle Model.

5.3.1 Introduction of a Design life-cycle Model

The literature review discussed a number of current design life-cycles that are used in academic work. It identified the design life-cycle models and the central core activities on which the design process is based. All the design life-cycle concepts had a common feature in having a structured design process.

Research in this area highlights a number of potential areas for the introduction of novel proposals in the design life-cycle; in particular in the manufacture of high complexity low volume products, as in the aircraft industry.

The importance of adopting a structured method when designing a product is clear in current academic work, however the current design models fail to handle this in a structured way so as to obtain a robust design. A further observation from the literature review was the lack of attention to the customer requirements within the current design life-cycles and how the design meets these as the product design matures. The author's solution is to introduce these highlighted areas into a new novel approach to the design life-cycle for aircraft manufacture, with the emphasis on how DFM can be structured and measured ensuring a robust design, while keeping the emphasis on the customer requirements and monitoring how close the design is to these throughout the design process.

5.3.2 Proposed Design Life-cycle

Taking into account the best features of the DLC's in chapter 2, a specific DLC is proposed for the design of complex products such as airframe manufacture. Today's industrial requirements lead to the development of products that satisfy customer requirements with a reduction in the DLC process to enable their product to have a scheduled or early entry into the market place. These requirements need to be met along with a producible design that will not bankrupt an organisation during manufacture due to excessive defect rates. Therefore, the design has to include DFM and design for ‘X’ concepts, (Kuo, C Huang,C.H. Zhang, H 2001). The DLC will have to analyse an increasing amount of complex data to produce a more cost-effective design along with the reduction of the DLC. More demands and information are placed on the DLC, these rarely replace existing demands to balance the design life-cycle duration, and therefore using the current DLC models may not be effective at delivering current industrial needs.

5.3.3 Proposed Design Life-cycle Core Drivers

The proposed DLC uses three main drivers to deal with the issue of it’s time span reduction with the addition of more complex data to analyse, these are detailed in Figure 5.3

Key Driver 1

The requirement definition needs to be the central structure of the whole process with a constant review of this through the process. This is especially important in an engineering environment, as the natural trait of most engineers is to drive themselves to a complex over-engineered solution. This may not only exceed customer requirements but will add time and cost to the design process and increase the likelihood of adding potential problems to other disciplines e.g. manufacturing or mass engineering.

Driving requirements through the design life-cycle will also help with the direction and control of information through the design period. Existing models show little focus on the requirements definition through the design process.

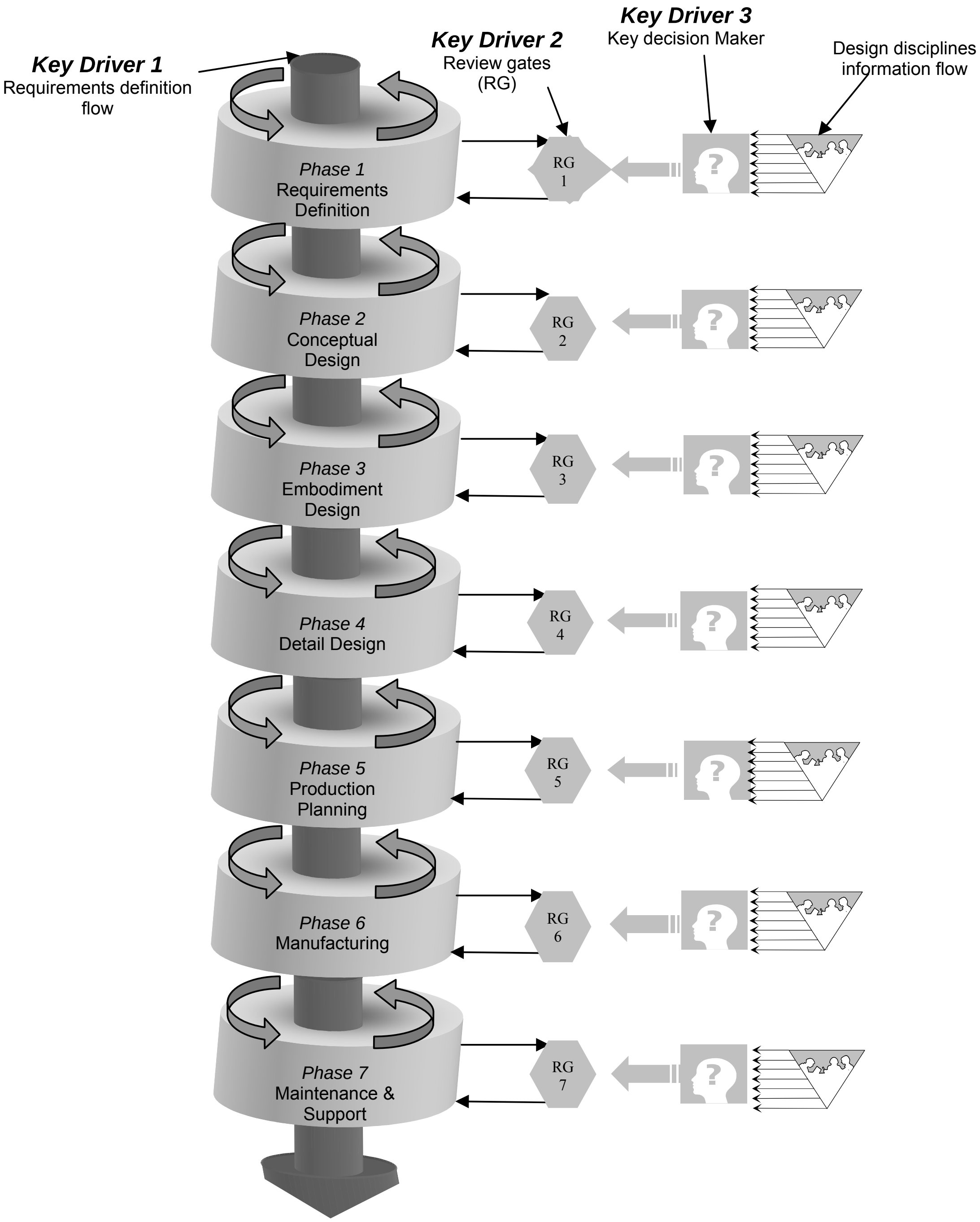

Figure 5.3 – Key Drivers for the Proposed Design Life-cycle

Key Driver 2

A review gate at each life-cycle phase will help structure the information flow through to the next phase. This will look at the outputs for the phase along with inputs from the relevant disciplines. This will help to reduce the risk of moving through the DLC with insufficient information thus ensuring a successful completion of the next phase. With the maintenance of pressure to ensure that the product meets the market at the desired time, there is a great risk of moving through the phases with immature information. The review gate process enables various disciplines in the DLC to voice any concerns of excessive risk in moving forward to the next phases in the cycle. This should be backed up with relevant data from the engineering data set.

Key Driver 3

To enable a reduction in time span of the DLC, there is need for an experienced lead engineer to be a review gate decision maker. They look at the outputs from the phases and the inputs from the disciplines and review these against the requirements definition before the design can progress to the next phase. Any information that is presented to the lead engineer should be substantiated. This helps control the flow of information through the design process, enabling a reduction in DLC. This driver helps to stabilise this decision point with the review gate controlled. This is a major element when designing such complex products, as not all the engineering disciplines can be completely satisfied that their entire requirements have been met. With this consideration in mind the key decision maker has to ensure which decisions are important to the customer requirements and that all risks are fully assessed.

5.3.4 Seven Phases of the Proposed Design Life-cycle

The design life-cycle will be based on seven phases, developed from the work of Pahl and Beitz (1996), forming a core structure of the design life-cycle. The proposed core structure is similar to many design life-cycle models, however the core design structure presented will assist in addressing the additional requirements that today's industry expects, discussed in section 1.2. This requires analysis of information in the phases along with the information flow through the phases, shown in figure 5.3, this will be structured and controlled by the requirements definition.

Phase 1 - Requirements Definition (RD)

These are the customer's requirements, which should be identified for each discipline along with delivery time, schedule requirements and any cost constraints.

Phase 2 - Conceptual Design (CD)

This phase looks at the product requirements and translates them into conceptual alternatives. Once these alternatives are decided they should be evaluated alongside current technologies that could develop from conceptual designs. These should be considered along with preliminary costs, estimated for the alternatives, ensuring that the design decisions fit with the requirements definition.

Phase 3 - Embodiment Design (ED)

The viable product concepts from the CD are enhanced into more clearly defined forms. From here, critical dimensions are specified and preliminary forms and sizing are defined such as component shapes and materials. The designs should also be evaluated against both technical and economic criteria as well as the requirements definition.

Phase 4 - Detail design (DD)

Within this phase, all data needed to complete the product are selected from the ED phase. The product’s geometry is completed, all dimensions are added, tolerances are specified and full design documentation is prepared.

Phase 5 - Production Planning (PP)

Production engineering plans; routings and process-specific parameters are specified. Machine tool and inspection programming occurs, cutting tools, tooling decisions are made and production procedures are written. In addition, quality control issues, logistics, purchasing and capacity issues are addressed.

Phase 6 - Manufacturing (MFG)

The product is manufactured using methods and procedures defined during PP. Product data is collected and analysed to update the design for manufacture data. Cost reduction initiatives are introduced which may incur design change.

Phase 7 - Maintenance and Support (M&S)

Both planned and unplanned maintenance is performed. Data should be collated to update design for manufacture information.

These core design phases, as in many models, look like a straightforward mechanistic process. However, when they are transferred into the industrial environment many sources of information have to be considered or are needed for various requirements. These should be considered when engineers are involved in an integrated product team within a concurrent environment.

Integrated product teams or cross-functional teams are teams working within a functional product based organisation. The key elements of an effective cross-functional team are its variety of skills, interdependence of work and delivery of common objectives, (Holland et al., 2000). The definition of a cross-functional team is a group of people who apply different skills, with a high degree of independence, to ensure the effective delivery of a common organisational objective.

When designing a large complex product it requires considerable expertise in many areas, with this in mind a collaborative engineering environment may be required. This is where the team members may be geographically distributed are virtually connected so the best engineering talent can be applied to the design effort regardless of physical location. In addition, a more efficient, higher quality design product is delivered by bringing together the best engineering talent with more up-to-date design and analysis Prasad et al. (1998) reviews this further.

5.3.5 Concurrent Engineering Review Gates and its Associated Risk

As discussed in the previous section the DLC operates in an environment, where each phase is not developed independently but concurrently with each other. This will assist in the reduction of the life-cycle but may increase risk in the decision process as detailed in Figure 5.4.

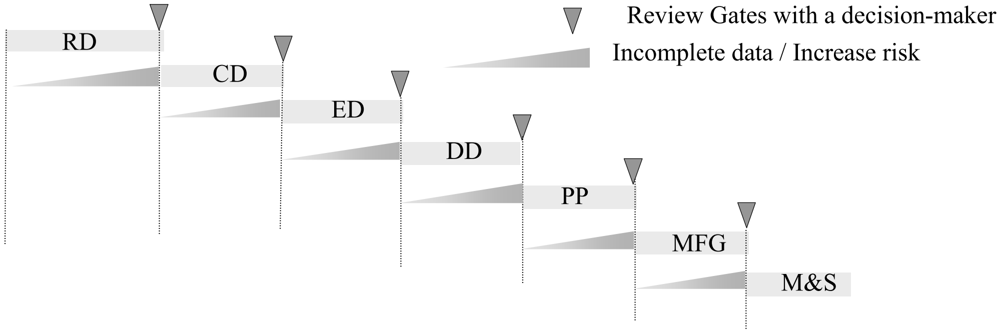

Figure 5.4 - Risk Introduced in a Concurrent Engineering Environment

During the development of this proposed design life-cycle the author has taken risk into consideration to ensure that the operation of the design life-cycle can work effectively within the environment. When in a concurrent environment, in most cases, there will be a degree of risk within the design life-cycle as information may not be considered completely mature until it passes through the design gate. For example, if the DD phase starts to look at the product's geometry configuration during the initial stages of the ED phase then potential risks may be contained in the preliminary work before the ED phases has exited its phase gate review. The possibility exists that the engineering work in DD may have to be restructured inline with the outcomes of the CD phase. However, this can be reduced by good communication through the integrated product team (IPT) and the effective use of a requirements definition tool. This will assist in the direction of the decisions through each phase. Cheng et al. (2003) and Nkasu and Leung (1995) also review the potential risks in the design process.

Each phase will develop outputs containing data from various disciplines; each will have their own requirements. For example manufacturing engineering will have to consider ease of manufacture, assembly and DFM requirements; design engineering may ask manufacturing to compromise on their requirements. The review gate cannot be passed, until the decision has been clarified. Within an industrial design environment it is a common scenario that a number of disciplines have conflicting requirements, it is essential that an experienced lead engineer acts as a decision-maker, looking at the global environment and not bias to one specific discipline. The most appropriate tool to reduce potential risk is the information flow of the requirement definition through the design process. Although many of the current design cycle models have the RD phases at the start of the DLC they do not make clear the potential this will introduce in the decision-making and risk reduction processes.

5.3.6 Practical Implementation

A genuine example of this is the mass on an airframe: the requirements definition would probably score this high as a customer requirement. Weber (1994) identifies that aircraft are weight critical; every pound of unnecessary aircraft structure weight reduces aircraft performance, aircraft payload, or the distance the aircraft can fly without refuelling.

Due to these reasons the requirements definition model will highlight this as a critical requirement and manufacturing may have to deal with a less cost-effective design, necessitating alternative cost reduction initiatives. An important factor of the proposed model is that the decision is recorded so when progressing through the life-cycle the manufacturing organisation understands the background to the decision and during any cost reduction exercises time is not being wasted re-clarifying this.

The example used can be equated into the manufacturing first time yield. If the expected yield was 98%, due to the decision in favour of weight, the effect on yield is a reduction to 90%, for every hundred products produced ten would be defective. If this information was not communicated through the DLC then this would have potentially severe consequences to the assembly line

As an example let us look at an airframe and the selection of fastener diameter between a skin and structure, shown in figure 5.5

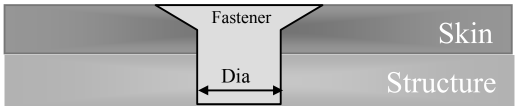

Figure 5.5 - Fastener diameter selection through an aircraft skin and structure.

What seems a relatively straightforward decision can have a complex network of dependencies. Firstly, the fastener load allowable needs to be known. This is the load the fastener can withstand before destruction occurs (involving the fastener supplier). The load in the area that the fastener can withhold needs to be derived. However to determine the loads in the specific area it will require information from the aerodynamic loads finite element model (FEM) and these will feed into the FEM of the aircraft. This will then feed information into a number of detailed FEMs, for the defined unit and specific area for the fasteners. Once the fastener size and quantity have been defined, other disciplines in the organisation will have requirements. Assembly manufacturing engineers may have problems with accessibility to install the fasteners, therefore, the pitching of the fasteners may vary. This has to be re-calculated to ensure the requirements can be met. The mass engineer needs to calculate the mass requirements and may request fewer fasteners or more fasteners to reduce the weight in the structure and skins. Each time a requirement is specified the load may have to be re-calculated. An experienced decision maker can reduce the design life-cycle by refining the process and considerably reducing the time taken by defining the best starting point within the phase. The proposed design life-cycle model shows the phase outputs and decisions feeding the gate with information. Disciplines will feed the delivery gate with either quantitative or qualitative data.

The development of a novel design evaluation tool by the author, discussed later in this chapter, will define the translation of data and help compare it to the customer requirements. A further key role in the DLC is that of business management who measure the performance, cost, schedule adherence etc. This design evaluation tool will establish the effect of the design in production so the manufacturing environment can start to prepare for the results the design will have, not only on manufacturing but on the business as whole, these results will be fed into the requirements definition.

The DLC should also take consideration of the product position within its life-cycle. For a new product the complete DLC should be followed, however there may be a requirement to develop the original design with pressure to reduce the DLC for cost reduction. In this case, the product design may be introduced at the embodiment stage where a new material or technology can enhance the outputs from the concept definition phase. The product may require a redesign due to cost reduction programmes in the manufacturing phase justifying a redesign of the product to aid manufacture; this should be introduced at the detail design phase.

These are typical examples of entries into the design phase and industry specific requirements that may dictate the entry level in the DLC, with the addition of the various entry points. The proposed DLC is illustrated in Figure 5.6.

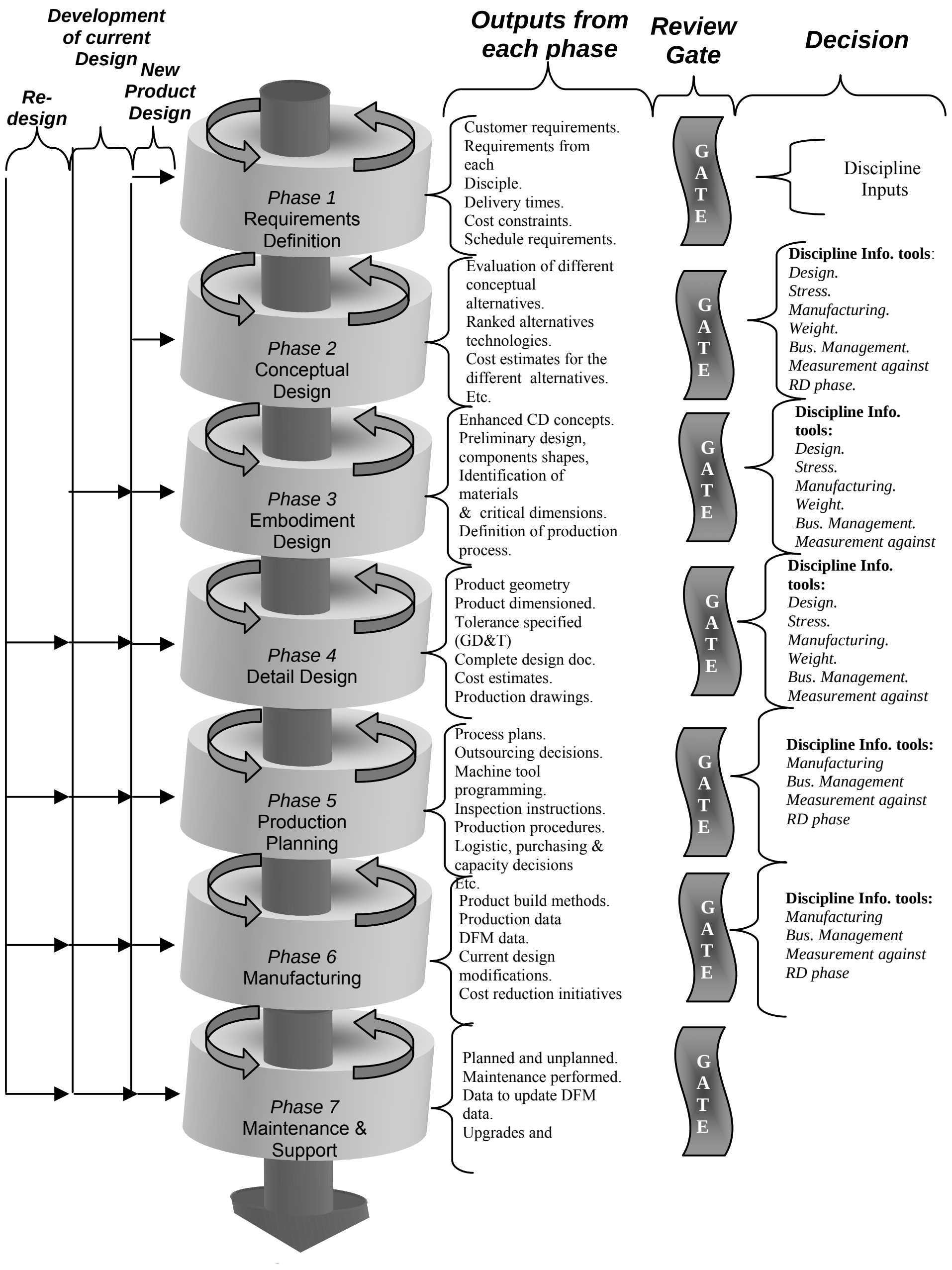

Figure 5.6 - Proposed Product Life-cycle

5.4 Key Characteristics within Design for Manufacturing

5.4.1 Key Characteristics

One of the major steps required in the design of a product is to identify the key characteristics (KCs). The Manufacturing Development Guide 1998 refers to key characteristics as design features for which variation significantly affects product performance, quality, cost or safety. This document was developed by a joint government and industry team, its aim being to provide guidance for *"weapon system acquisition"*.

The selection of KCs is one of the key areas in the valuation of the design. In aircraft design and manufacture there are many different processes, products and parameters that are combined to produce the final designed product. The task to identify and monitor them all would be an extremely large one, impacting on costs and the overall life-cycle of the product. It is therefore important to analyse only the most relevant characteristics, those that affect the performance, quality, cost or safety of the product.

Once the KCs have been defined they can be evaluated using existing methods such as statistical process control measures to calculate indices such as mean, standard deviation, CP & CPK values, the detail of which is discussed in section 5.5.2. These indices can be useful when interpreted by a trained engineer; however more detailed analysis of these KC's is required to transfer design information into useable parameters that can assess the cost efficiently and the adherence to customer requirements.

5.4.2 Selection of the Key Characteristics

The importance of selecting the correct KCs in the design of a product has been highlighted. The selection of the KCs will be developed through the DLC, maturing in the design development phase. To help highlight KC features, an example of a typical aircraft component is used, a rib, similar to that shown in appendix 1.

Component datum features;

- Flatness, this controls the main datum;
- Hole diameter, this controls the secondary datum;
- Hole position and diameter, this controls the third datum;

These will be defined as KCs as they are the main datums[1] on the component. The assembly fixture will restrain the component on these locations so the relationship to its interfacing components in the overall assembly can be established. This will enable manufacturing engineers to establish its location digitally (discussed later in the chapter) so before the individual component is assembled with its mating parts the fitment can be verified. These datums[1] form the base of the product, tolerances and location, hence critical to the success of the overall assembly; therefore the author has identified these as KCs.

Looking at the example of a rib there will be a number of features that will mate or connect with other parts in the assembly, these are called interfacing features. These are the most critical of the features, for example, if there was a stiffening flange in the centre of the channel and its position varied it would not stop the component being loaded into the jig, as it does not interface with corresponding parts.

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[1] Data is a plural of datum. In surveying and civil engineering, where datum has specialised senses, the plural form is datums. – Unabridged Dictionary 2006

Therefore, would not meet the criteria of a KC. The typical features, of a rib, that would interface with other parts are highlighted below;

Component features:

- Surface profile – interfacing with mating spars. Three surfaces in each side, six in total
- Surface profile – lower, this controls the skin to structure interface for the lower surface
- Surface profile – upper, this controls the skin to structure interface for the upper surface

For example these features need to be controlled to avoid incorrect location on assembly. If the surfaces were outside of the tolerances, then one of two issues would occur. The component would be too large to fit the assembly or the component would be too small, hence a large gap in the structure resulting in a weak assembly.

5.5 Design for Manufacture, Evaluation of the Design for its Manufacturability.

5.5.1 Design Evaluation tool

The literature search has highlighted that even with technical advancement in the design of a product, mostly due to the advancements in computer technology; there is still a clear need for the design to be evaluated in terms of its manufacturability. The designers use Computer Aided Design (CAD) tools to aid them in creating a 3D view of the product enabling them to introduce the product into the more complex environment of the assembly. The designer can *"fly through"* the assembly using the computer technology and if designing an airframe, can view the interactions of various systems and structure. This initial design of the product is just the preliminary use of current computer technology, this digital environment, in today's aircraft design, flows through the complete design life-cycle to the final assembly of the product. This is illustrated in figure 5.7

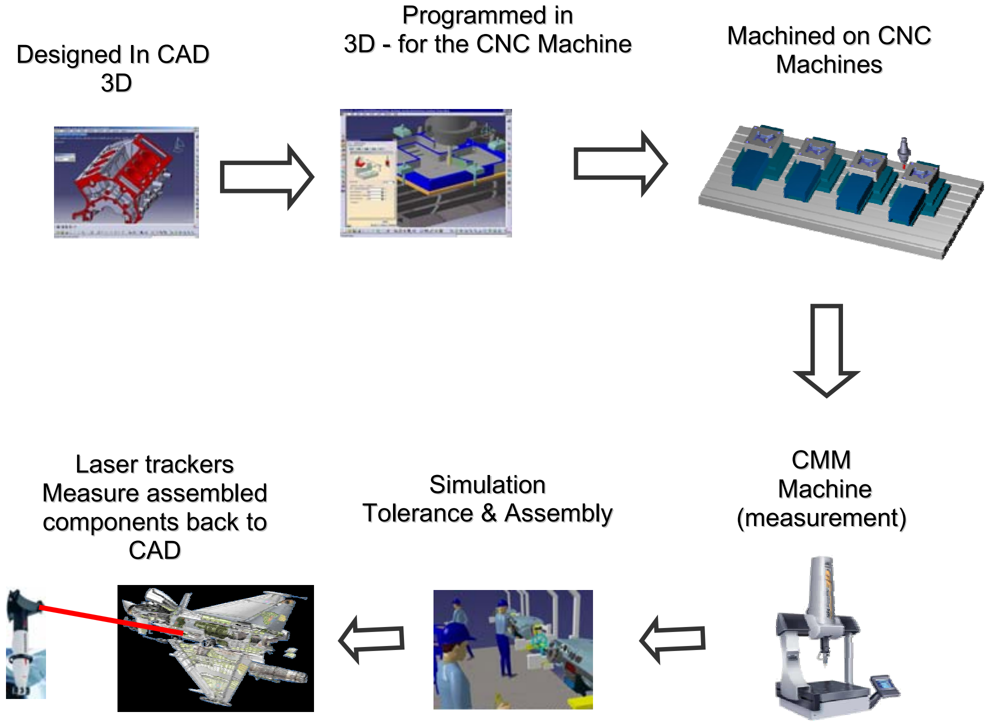


Figure 5.7 – Digital Environment, in the design life-cycle

This digital environment starts with the detail design phase, phase 4 in figure 5.6 of the proposed product life-cycle. Once the 3D solid has been produced the machine programmers produce a program for the computer controlled milling machine. When the component has completed manufacture, it is inspected on a Coordinate Measurement Machine (CMM). There are additional simulation tools that can be used to undergo ergonomic studies to stimulate the component's fit and access during the assembly process. During the assembly, tools like laser tracker machines translate the computer 3D model of the component to its actual position in assembly. All these tasks are completed in a digital environment with little or no manual intervention. Chapter 2 highlights the fact that there is no current computer based model that can evaluate the complete robustness of the design during the design life-cycle. Boothroyd and Dewhurst's (2006) design for assembly software was discussed in chapter two, where there are many cost savings and advantages to the design. Whilst Boothroyd's and Dewhurst's software package evaluates both the part design and the overall design of the assembly by identifying unnecessary parts in an assembly and determining the assembly times and costs, the author has identified that defect costs are not measured during the design of the product. These defect costs are the associated costs to bring manufactured products back to the designed intent. There are many extra costs associated with defects and due to the highly complex natural of aircraft, these are exacerbated and rarely measured within the industry design phase.

This void is filled by the introduction of a novel design evaluation tool in the design life-cycle developed as part of the research project. As discussed previously in the chapter, to enable the reduction of defect costs from the initial concepts of the design through to manufacture, a structured process needs to be introduced. Through this process there are many decisions that have to be made to ensure that the product concurs with the customer requirements. Various computer based tools are using to aid these decisions for engineering disciplines such as design, structural analysis, weights etc, whilst the manufacturing engineers have to estimate and rely on their *"best guess"* as to the effect the design would have on the product and the overall company. The design evaluation tool evaluates both the design of the individual and substructure components and the assembly. The data is then combined together to give an overall view of the defect cost and the main contributors to the additional cost. It also gives the design team information as to which areas of the design should be scrutinised to reduce the overall cost. The tool has been designed to work inside the proposed design-life-cycle model, discussed earlier in this chapter. It is therefore an integrated part of the process, as with many other software tools for engineering disciplines. The data that is required for the design evaluation tool to produce its output is data that is used in the in the design life-cycle to enable its progression through the gates at each phase. This was carefully considered prior to the design of the tool as it is essential to ensure that the design life-cycle phase is not extended due to irrelevant external factors, which would lead to late delivery of the product in the market place. Typical output data is shown in figures 5.8 and 5.9.

5.5.2 The design evaluation tool’s input and outputs

The design evaluation tool requires process capability data from the manufacturing organisation along with selected design features to achieve the manufacturability measurable, the outputs from the design evaluation tool. The author explains in detail, later in the chapter, how the design evaluation tool uses these inputs to calculate the manufacturability of the design.

To assist the reader in the understanding of this complex analysis of design data the author lists firstly the various inputs that the design evaluation tool requires, then the various outputs from the individual components and the assembly of them. Figure 5.8 and 5.9 show, highlighted in red, how these outputs are structured in the tool.

The Design Evaluation Tool's Inputs, for the individual structural components and assembly processes

Key features;

These are the main areas of the product which are linked to the customer requirements

Quantity;

This is the quantity of key features within the product; it contributes to the overall opportunities for defects.

Upper specification limit;

The upper specification limit is the upper tolerance range that the designer has specified during the detail design phase.

Lower specification limit;

The lower specification limit is the lower tolerance range that the designer has specified during the detail design phase

Standard deviation and mean;

These are calculated from the process capability data held within the background of the tool.

Number of products components;

This defines the number of products that will be used in the assembly

The Design Evaluation Tools Output Data, for the individual structural components.

CP and CPK;

These are process capability indices that are calculated from various input data.

Quality Measures

Defects per unit;

How many defects have occurred on the unit being evaluated?

Opportunities for Defect;

This the amount of potential defects which could arise on the product

Yield;

This is know as the first time yield and indicates the potential for the product to be without defects.

Defects per million opportunities;

The number of defects that would occur if one million components where produced.

Sigma;

This indicates the capability of the processes, discussed in chapter 2

Cost data

Repair;

The repair cost is the extra cost associated to the product when the design limits of the key features are exceeded.

Non Conformance;

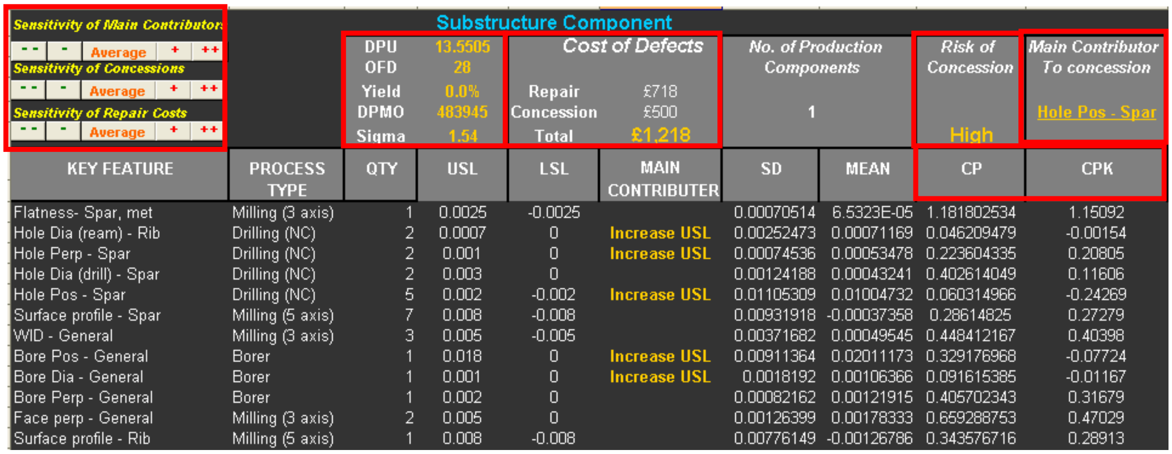
This cost is related to the engineer’s time to address the non-conformances of a product and the associated paper work.

Risk of Concession;

This indicates the possibility of the designed product having to have a non conformance issued for the product to be used on the assembly. This is indicated by categories, low, medium and high.

The main contributor;

This important output highlights to an engineer which design feature contributes the largest amount of defect cost to the product being analysed.



Substructure Component

DPU 13.5505
OFD 28
Yield 0.0%
DPMO 483945
Sigma 1.54

Cost of Defects
Repair £718
Concession £500
Total £1,218

No. of Production Components 1

Risk of Concession High

Main Contributor To concession Hole Pos - Spar

KEY FEATURE	PROCESS TYPE	QTY	USL	LSL	MAIN CONTRIBUTER	SD	MEAN	CP	CPK
Flatness- Spar, met	Milling (3 axis)	1	0.0025	-0.0025		0.00070514	6.5323E-05	1.181802534	1.15092
Hole Dia (ream) - Rib	Drilling (NC)	2	0.0007	0	Increase USL	0.00252473	0.00071169	0.046209479	-0.00154
Hole Perp - Spar	Drilling (NC)	2	0.001	0	Increase USL	0.00074536	0.00053478	0.223604335	0.20805
Hole Dia (drill) - Spar	Drilling (NC)	2	0.003	0		0.00124188	0.00043241	0.402614049	0.11606
Hole Pos - Spar	Drilling (NC)	5	0.002	-0.002	Increase USL	0.01105309	0.01004732	0.060314966	-0.24269
Surface profile - Spar	Milling (5 axis)	7	0.008	-0.008		0.00931918	-0.00037358	0.28614825	0.27279
WID - General	Milling (3 axis)	3	0.005	-0.005		0.00371682	0.00049545	0.448412167	0.40398
Bore Pos - General	Borer	1	0.018	0	Increase USL	0.00911364	0.02011173	0.329176968	-0.07724
Bore Dia - General	Borer	1	0.001	0	Increase USL	0.0018192	0.00106366	0.091615385	-0.01167
Bore Perp - General	Borer	1	0.002	0		0.00082162	0.00121915	0.405702343	0.31679
Face perp - General	Milling (3 axis)	2	0.005	0		0.00126399	0.00178333	0.659288753	0.47029
Surface profile - Rib	Milling (5 axis)	1	0.008	-0.008		0.00776149	-0.00126786	0.343576716	0.28913

Figure 5.8 – Design Evaluation Tool’s Output for Substructure Components

The Design Evaluation Tool’s Output Data, for an assembled product

CP and CPK;

These are process capability indices that are calculated from various input data. Some features in the assembly are measured using attribute data.

Quality Measures

Defects per unit;

The number of defects occurred on the unit being evaluated.

Opportunities for Defect;

This the amount of potential defects could arise in the assembly

Yield;

This is know as the first time yield and indicates the potential for the product to be without defects.

Defects per million opportunities;

The number of defects that would occur if one million assemblies where produced.

Sigma;

This indicates the capability of the processes, discussed in chapter 2

Cost data

Repair;

The repair cost is the extra cost associated with the product when the design limits of the key features are exceeded.

None Conformance;

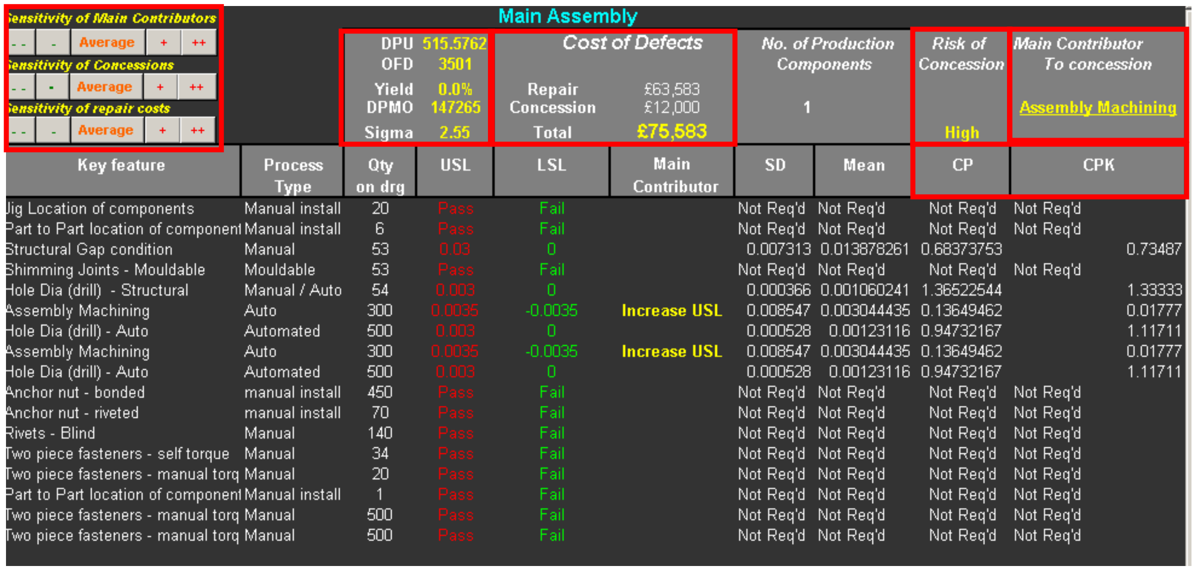
This cost is related to the engineer's time to address the none conformances of a assembly and the associated paper work.

Risk of None Conformance;

This indicates the possibility of the designed assembly having to have a none conformance issued for the product to be used on the assembly. This is indicated be categorises, low, medium and high.

The main contributor;

This important output highlights to an engineer which design feature contributes the largest amount of defect cost to the product being analysed.



Main Assembly

Sensitivity of Main Contributors
- - | - | Average | + | ++

Sensitivity of Concessions
- - | - | Average | + | ++

Sensitivity of repair costs
- - | - | Average | + | ++

DPU 515.5762
OFD 3501
Yield 0.0%
DPMO 147265
Sigma 2.55

Cost of Defects
Repair £63,583
Concession £12,000
Total £75,583

No. of Production Components
1

Risk of Concession
High

Main Contributor To concession
Assembly Machining

Key feature	Process Type	Qty on drg	USL	LSL	Main Contributor	SD	Mean	CP	CPK
Jig Location of components	Manual install	20	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Part to Part location of component	Manual install	6	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Structural Gap condition	Manual	53	0.03	0		0.007313	0.013878261	0.68373753	0.73487
Shimming Joints - Mouldable	Mouldable	53	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Hole Dia (drill) - Structural	Manual / Auto	54	0.003	0		0.000366	0.001060241	1.36522544	1.33333
Assembly Machining	Auto	300	0.0035	-0.0035	Increase USL	0.008547	0.003044435	0.13649462	0.01777
Hole Dia (drill) - Auto	Automated	500	0.003	0		0.000528	0.00123116	0.94732167	1.11711
Assembly Machining	Auto	300	0.0035	-0.0035	Increase USL	0.008547	0.003044435	0.13649462	0.01777
Hole Dia (drill) - Auto	Automated	500	0.003	0		0.000528	0.00123116	0.94732167	1.11711
Anchor nut - bonded	manual install	450	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Anchor nut - riveted	manual install	70	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Rivets - Blind	Manual	140	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Two piece fasteners - self torque	Manual	34	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Two piece fasteners - manual torq	Manual	20	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Part to Part location of component	Manual install	1	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Two piece fasteners - manual torq	Manual	500	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd
Two piece fasteners - manual torq	Manual	500	Pass	Fail		Not Req'd	Not Req'd	Not Req'd	Not Req'd

Figure 5.9 – Design Evaluation Tools Output for the Overall Assembly

5.5.3 Process Capability Data in the Design Evaluation Tool

Many of the outputs that are generated from the design evaluation tool are from process capability data that is held within the tool. This is commonly known as statistical process control (SPC) which is a statistically based approach for monitoring, controlling, evaluating and analysing a process. SPC's aim is to monitor and try to achieve a stable process output from a product, monitoring the level of variation and meeting the design specification limits. It is important to note that the aim of SPC is to try to achieve process stability; this should be completed prior to process improvement initiatives.

The design evaluation tool is not a replacement of SPC analysis because it assumes that improvement teams are undertaking projects to reduce the amount of variation in the manufacturing process capability data in parallel. The more the manufacturing processes are in control the less it will affect the product cost. What the design evaluation does do, however, is to highlight areas in the product design for the improvement teams to focus on the major contributors that affect the end product.

The tool holds two types of process capability data, variability and attributes data:

Attribute data

In attribute data, each item of data is classified as belonging to one of a number of categories; in this case there are just two categories. The data collation used is where a number of components or features are inspected and classified as either inside or outside the design specification. In the design evaluation model the only area of the product where this is used is on the assembly, where little variable data can exist, e.g. a component will either fit in the assemble fixture or not, a fastener will either fit in a hole or not.

Variable Data

Variable data is where the data is measured on a continues scale. This is the extensive type of data used by the design evaluation tool. Each key feature highlighted has process capability data that is calculating the processes standard deviation which is transferred into the evaluation of the design. For example surface profile data, as shown in figure 5.10, numerous inspection points are taken on a CMM from the surface of the components. These points are then listed and a design specification is introduced. The points are from numerous products from previous manufactured components making up the process capability data. The data is a direct link from the CMM raw output file, a detailed review of the data was undertaken to remove the special causes.

Within SPC special causes of variation that are acute or not part of the process design can be highlighted and discarded is required. Using this approach a number of points were removed to try to give a representative view of the process capability of the key features. Once the data has been scrutinised it is then collated in the form of a frequency and a histogram graph. The data is then used to formulate the standard deviation and mean for each process, these results are transferred to the design evaluation model as the basis for further calculations.

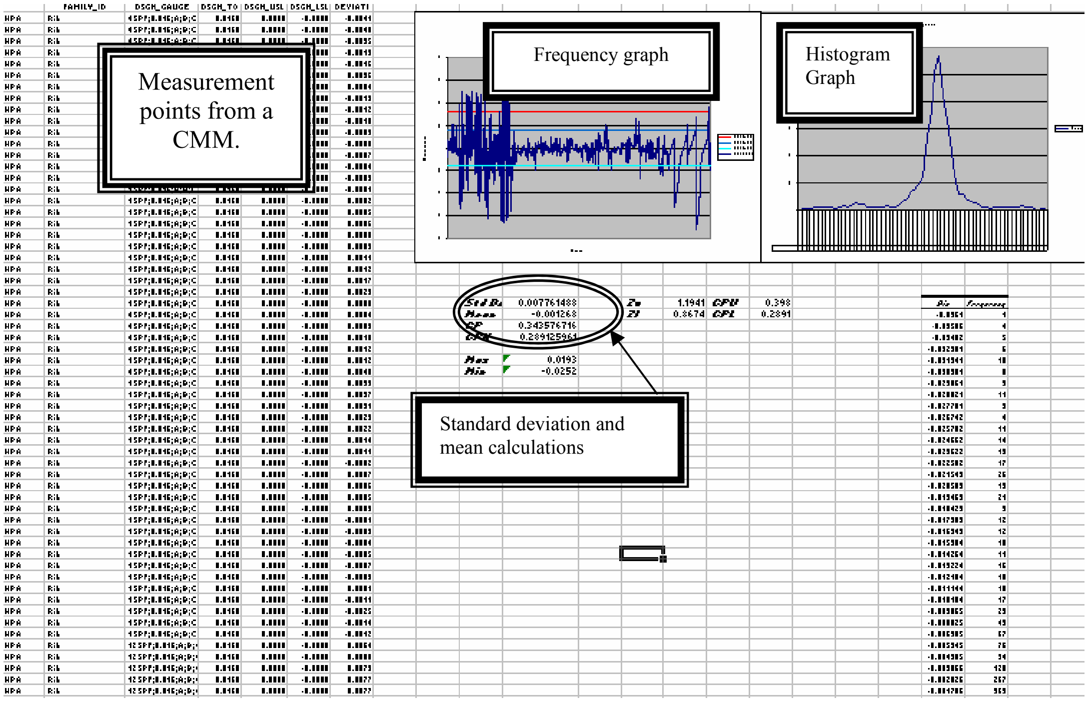


Figure 5.10 – Process capability data in the design evaluation tool showing surface profile measurements.

A summary of the process capability data that is held to support the evaluation of the design can be seen as follows:

Metallic Components

Bore, diameter	Variable data
Bore, perpendicularity	Variable data

Bore, position	Variable data
Face, perpendicularity	Variable data
Flatness, Rib	Variable data
Flatness, Spar	Variable data
Hole diameter, pilot holes	Variable data
Hole diameter, drill, Rib	Variable data
Hole diameter, drill, Spar	Variable data
Hole diameter, ream, Rib	Variable data
Hole diameter, ream, Spar	Variable data
Hole perpendicularity, Rib	Variable data
Hole position, Rib	Variable data
Hole position, Spar	Variable data
Surface profile dimension, Rib	Variable data
Surface profile dimension, Spar	Variable data
Width dimension	Variable data

Non-metallic components

Edge of part dimension, Skins	Variable data
Edge of part dimensions, Spars	Variable data
Flatness, Skin	Variable data
Hole diameter, drilling	Variable data
Surface profile dimension, Spar	Variable data
Skin Thickness	Variable data

Assembly processes

Bonding anchor nuts	Attribute data
Riveting anchor nuts	Attribute data
Assembly Machining	Variable data
Hole Diameter, drilling on the structure	Variable data
Hole Diameter, drilling on a machining	Variable data
Jig Location of components	Attribute data
Part to Part location of components	Attribute data
Application of blind Rivets	Attribute data
Application of standard rivets	Attribute data
Shimming Joints with moldable shim	Attribute data
Shimming Joints with solid shim	Attribute data
Structural Gap condition	Attribute data
Two piece fasteners, manual torque	Attribute data
Two piece fasteners, self torque	Attribute data

5.5.4 Calculations in the Design Evaluation Tool.

The aim in this section is to discuss the calculations in the design evaluation tool in a structured manner, starting from the process capability data that resides in the model. This is the core base of the calculations for the design evaluation; its structure is discussed in the previous section. To aid with the clarity of this section one of the KC's in the process capability data will be used (surface profile tolerance of ribs). The detail of this is show in appendix 1.

To relate this data to the design evaluation of the component two statistical calculations have to be derived. The suffix at the end of each title can be related to the section of the design evaluation tool in figure 5.11.

The mean or arithmetic average - 1

This is simply the average of the observations, the sum of all the measurements divided by the number of the observations.

Using the data from the selected KC, above, the mean is calculated to be:

$\sum$x = the total value of the data points

n = the number of data points

$$\bar{x} = \frac{\sum x}{n}$$

$$\bar{x} = \frac{-5.0106}{3952}$$

$$\bar{x} = -0.00126$$

Standard deviation - 2

The standard deviation takes all the data into account and is a measure of the deviation of the measurements from the mean. If a sample is being used to estimate the spread of the process, then the sample standard deviation will tend to under estimate the standard deviation of the whole process. This bias is particularly marked in small samples. To correct the bias, the sum of the squared deviations is divided by the sample size minus one

Using the same key feature the standard deviation is calculated as follows:

xi = the data values

$\bar{x}$ = sample mean

n = sample size

$$\sigma = \sqrt{\frac{\sum (xi - \bar{x})^2}{n-1}}$$

$$\sigma = \sqrt{\frac{0.2380}{3952-1}}$$

$$\sigma = 0.00776$$

Once the mean and the standard deviation have been derived from the process capability data, the design evaluation tool can begin its calculation process.

Process Capability Indices

A process capability index is a measure relating the actual performance of the process to its specified performance. The total variation of a process output for a normal distribution is usually termed as six sigma which means that most of the process capability data falls within +/- 3 standard deviations from the mean. Process capability compares that total variation of 6 standard deviations against the design specified limits. The design evaluation tool calculates two process capability indices.

Cp Index - 3

Most companies try to have a minimum Cp of 1.33, this means that 75% of the inspected points of a feature lie within the design specified tolerance, therefore the general assumption is made that even if the process changes slightly it has a higher probability that it will not produce products out of specification.

In order to manufacture the key processes within the designed specification, the difference between the upper specification Limit (USL) and the lower specification limit (LSL) must be less than the total process variation. Therefore, a comparison of six standard deviations within USL and the LSL gives a process capability index, known as Cp of the process. The C in Cp defines the capability, the p depicts the process.

USL = upper specification limit

LSL = lower specification limit

σ = sigma or a standard deviation

$$Cp = \frac{USL_1 - LSL_1}{6\sigma}$$

$$or \frac{Specifactionwidth}{processwidth}$$

$$Cp = \frac{0.008 - (-0.008)}{0.04656}$$

$$Cp = 0.3436$$

Cpk Index - 4

This index looks at both process variations and the centring, this is widely accepted as a means of communicating process capability. It divides the total variation of the process in half and compares each half to how far the process average is from the upper specification limit and then lower specification limit. These are referred to Cp upper (Cpu) and Cp lower (Cpl). They relate the difference between the process mean and the upper and the lower specification limits respectively halving the total process variation, the overall process Cpk is the lower value of Cpu & Cpl. If the process mean ($\bar{x}$) is centred in the design specification then Cpu = Cpl. The aim of Cpk is similar to that of Cp, a process capability greater than 1.33, where the C indicates the capability, p for process and k is katavori, Japanese for deviation or offset. If $\bar{x}$ lies outside of the design specification, then the Cpk will be negative. In contrast, Cp will never be negative even if the entire distribution lies outside the specification. There could be a situation that a process with Cp of 1.333 produced only nonconforming products, in the case of Cpk this would not occur.

Zu = Z upper

Zl= Z lower

$$Cpk = \frac{\text{ZMin}}{3}$$

$$Zu = \frac{USL - \bar{x}}{\sigma}$$

Or $$Zu = \frac{\text{upper specification limit – process mean}}{\text{Standard deviation}}$$

$$Zl = \frac{\bar{x} - LSL}{\sigma}$$

Or $$Zl = \frac{\text{process mean - lower specification limit}}{\text{Standard deviation}}$$

This can be calculated on the key feature used previously – 1,2 & 3

$$Zu = \frac{0.008 - (-0.00126)}{0.00776}$$

$$Z\ Upper = 1.19 \quad \textbf{(-5)}$$

$$Zl = \frac{-0.00126 - (-0.008)}{0.00776}$$

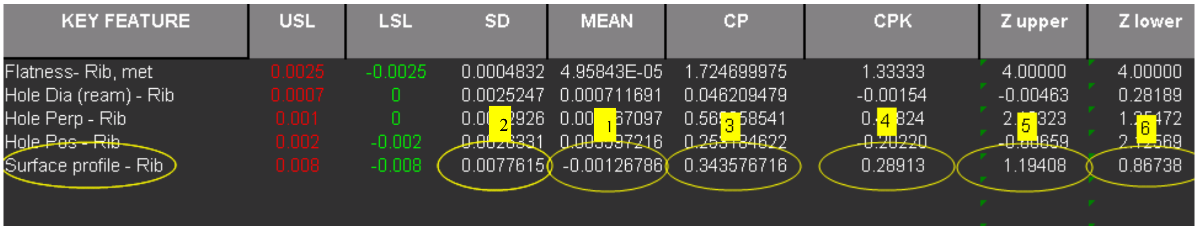
$$ZLower = 0.868 \ \textbf{(-6)}$$

Therefore the Cpk of the surface profile process capability data is;

$$Cpk = \frac{0.868}{3}$$

$$Cpk = 0.289$$

Figure 5.11 highlights the calculations produced by the design evaluation tool. The numbers correspond to those on the formulas above.



KEY FEATURE	USL	LSL	SD	MEAN	CP	CPK	Z upper	Z lower
Flatness- Rib, met	0.0025	-0.0025	0.0004832	4.95843E-05	1.724699975	1.33333	4.00000	4.00000
Hole Dia (ream) - Rib	0.0007	0	0.0025247	0.000711691	0.046209479	-0.00154	-0.00463	0.28189
Hole Perp - Rib	0.001	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hole Pos - Rib	0.002	-0.002	[illegible]	[illegible]	[illegible]	-0.20220	[illegible]	[illegible]
Surface profile - Rib	0.008	-0.008	0.0077615	-0.00126786	0.343576716	0.28913	1.19408	0.86738

Figure 5.11 – Design Evaluation tool calculations

Using the raw data from the inspection of previous products, for the selected key feature, calculations of the mean and standard deviation can be established along with the process capability indices Cp and Cpk. These indices are a powerful estimate for a trained manufacturing engineer to establish how robust the design is. However, these are little use to the design team to establish the robustness of the design. The design team require clear data so they can measure the effectiveness of the design and the long term effect it will have on the project and the overall business requirements.

Design for manufacture data needs to be presented in the design life-cycle to establish whether the customer requirements have been met and for the manufacturing engineer to affect the design as it passes through the design stage gates, this is discussed in previous sections in this chapter. As current research only offers data in terms of Cp and Cpk indices, this gives the manufacturing engineering in the design team little weight to their argument for a design change.

During the design of aircraft there are many disciplines that have similar concerns, weight engineers can easily calculate the weight arising from the design and structural engineers can calculate the strength of components. These are examples of tangible data that can be produced from the various disciplines, leaving the manufacturing engineers with little tangible defence to change the design to aid manufacture.

Using current process capability indices, if the manufacturing engineer feels there is a potential issue with the surface profile tolerance and had a preference to increase or decrease the design, USL and LSL would change. The effect would be the mean and the standard deviation would remain the same with the Cp & Cpk changing:

$$Cp = \frac{0.010-(-0.010)}{0.04656}$$

$$Cp = 0.4295$$

$$Zl = \frac{-0.00126 - (-0.010)}{0.00776}$$

$$ZLower = 1.126$$

$$Zu = \frac{0.010 - (-0.00126)}{0.00776}$$

$$Zu = 1.45$$

$$Cpk = \frac{1.126}{3}$$

$$Cpk = 0.375$$

It can be seen from the above example that with the increase in tolerance the process indices increase, which means there is less chance of producing defects. However, it remains that armed with this data it still gives manufacturing engineers little leverage over other disciplines in the design team to change the design e.g. the Cpk will increase from 0.289 to 0.375.

With this taken into consideration further calculations will manipulate the data to link design for manufacture data to customer requirements, hence producing more tangible manufacturing engineering data in the design life-cycle.

So far the data evaluated of the key feature has been inside the design tolerance. If we look at the amount of potential defects, i.e. points that fall outside of the design tolerance, manufacturing engineering can start to produce more tangible data that can be used by engineering within the design team. To establish the potential components that may be defective one needs to find the Pz value, explained in figure 5.12. Using the Z values from calculating Cpk values the Pz value can be established.

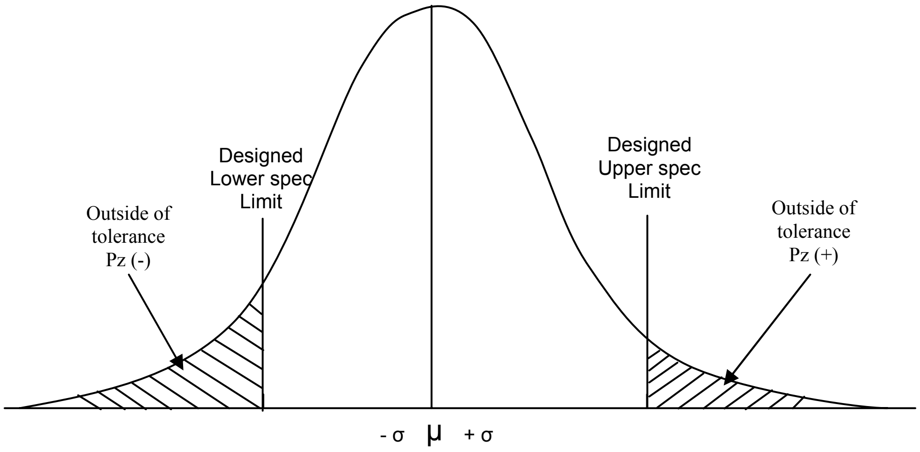


Figure 5.12 – Points outside the design limit, Pz values

Where:

USL = upper specification,	0.008
LSL = lower specification,	-0.008
$\bar{x}$ = sample mean,	-0.00126
σ = Estimated process standard deviation,	0.00776

Z = The number of standard deviations between the designed specification limits and the mean

$$Zupper = \frac{USL - \bar{x}}{\sigma}$$

ZUpper = 1.19

$$Zlower = \frac{\bar{x} - LSL}{\sigma}$$

Zlower = 0.868

Once the Z value has been defined the area under the curve for those points that are outside of the design specification needs to be calculated. To achieve the Z values they are compared to the table in appendix 3, this table is highlighted in (Oakland 1999). The mathematical equation for the normal curve (alternatively known as the Gaussian distribution) is;

$$y = \frac{1}{\sigma\sqrt{2\Pi}} e^{-(x-\bar{x})^2/2\sigma^2}$$

Where:

y = height of curve at any point x along the scale of the variable

σ = standard deviation of the population

$\bar{x}$ = average value of the variable for the distribution

π = ratio of circumference of a circle to its diameter (π = 3.1416)

Where, Oakland states, if z = (x- $\bar{x}$) / σ , then the equation becomes:

$$y = \frac{1}{\sigma\sqrt{2\Pi}} e^{-z^2/2^2}$$

$$\text{Constant} = \frac{1}{\sqrt{2\Pi}}$$

Oakland chooses the constant to ensure that the area under the curve is equal to unity, or probability 1.0. This allows the area under the curve between any two values of z to represent the probability that any item chosen at random will fall between the two values of z. The values given in appendix 3 show the proposition of the process output beyond a single specification limit that is z standard deviation units away from the process average. Oakland highlights that the process should be in statistical control to ensure the best results.

The table in appendix 3 is used to estimate the percentage of area that is outside of the design specification:

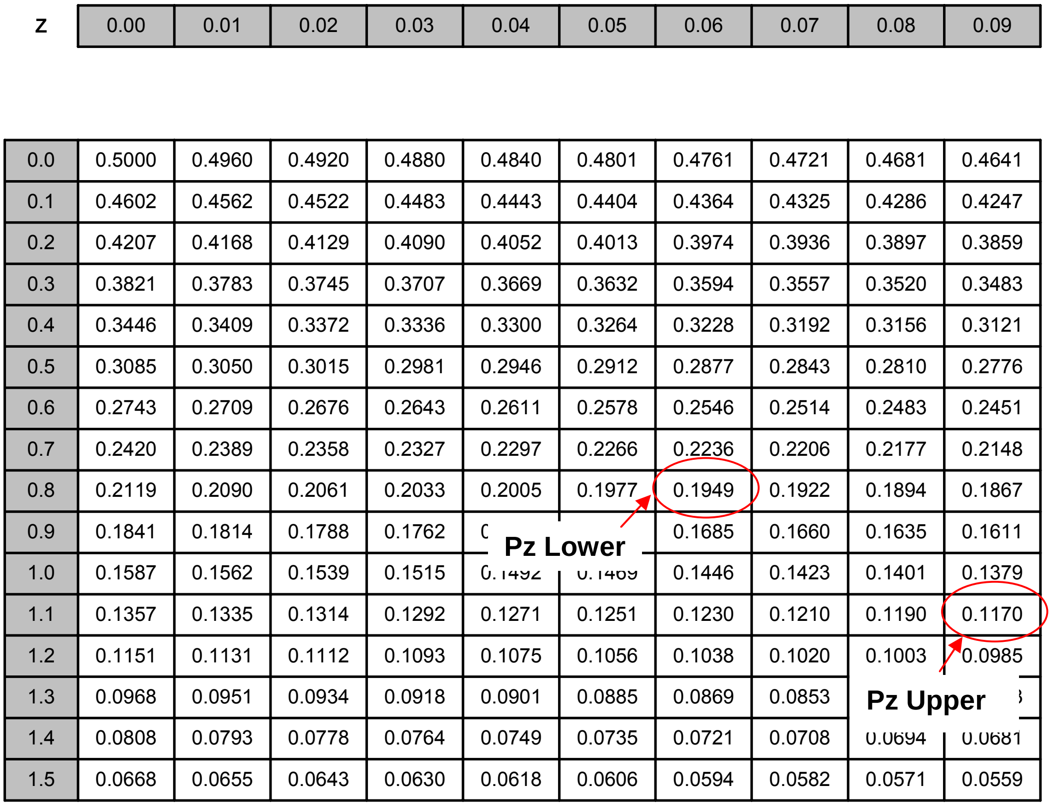
Step1

Take the Z value calculated previously and find the first two corresponding numbers listed down the left hand column of the data table, this will give a horizontal position on the table

Step 2

Trace along the horizontal and vertical positions to the point they met.

This is shown in figure 5.13



z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641
0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
0.7	0.2420	0.2389	0.2358	0.2327	0.2297	0.2266	0.2236	0.2206	0.2177	0.2148
0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
0.9	0.1841	0.1814	0.1788	0.1762	[illegible]	[illegible]	0.1685	0.1660	0.1635	0.1611
1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	[illegible]	[illegible]
1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559

Figure 5.13 – Selection of Pz values, from the table representing the proportions under the tail of the normal distribution, (Oakland 1999).

Once these values have been selected they are multiplied by 100 to derive the percentage under the section of the curve.

Pz upper = 0.117 x 100 = 11.7% of defects.

Pz lower = 0.1949 x 100 = 19.4% of defects.

The method discussed above is not conducive to an automated design evaluation tool which is essential if the design evaluation tool is going to produce *"real time"* data to the design team. To ensure this, a formula has to be derived to ensure a direct comparison between the Z and Pz values. To establish this, the table in appendix 3 has been formulated into a graphical format, shown in figure 5.14.

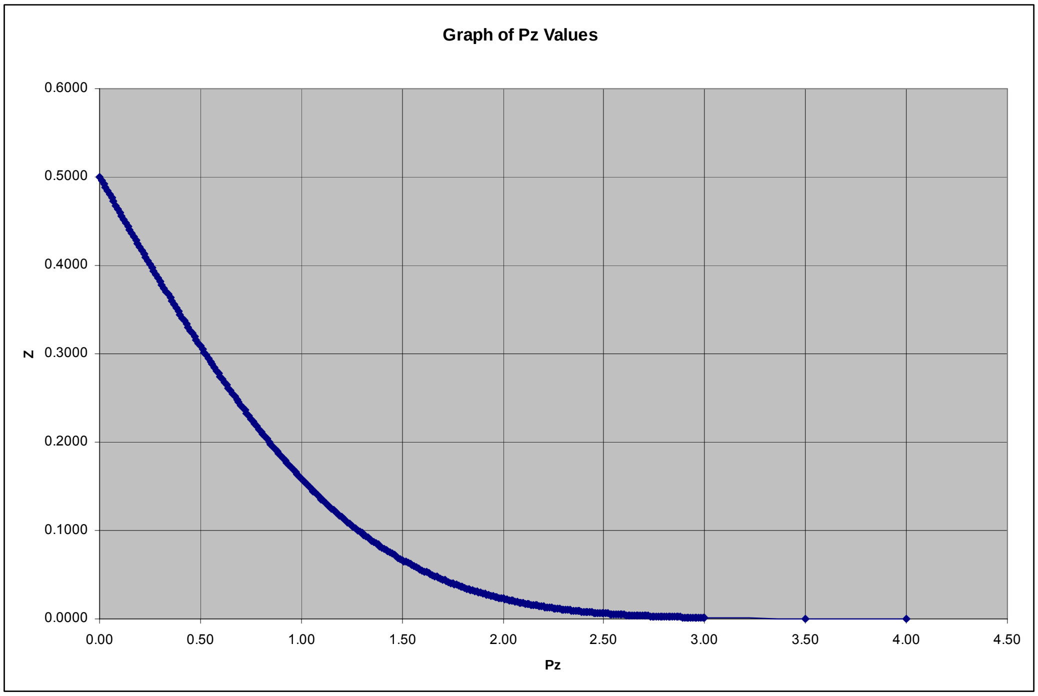


Figure 5.14 – A graphical representation from the table, representing the proportions under the tail of the normal distribution, Oakland 1999.

Research in this area concluded that a 12th order polynomial should be used to best fit the curve in figure 5.14.

Polynomial regression fits data to this equation;

$$Y = a_0 + a_1 x^1 + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 + a_6 x^6 + a_7 x^7 + a_6 x^6 + a_7 x^7 + a_8 x^8 + + a_9 x^9 + a_{10} x^{10} + a_{11} x^{11} + a_{12} x^{12}$$

Any number of terms can be included. If you stop at the second (a_1) term, it is called a first-order polynomial equation, which is identical to the equation for a straight line. If you stop after the third (a_2) term, it is called a second-order, or quadratic, equation. If you stop after the fourth term, it is called a third-order, or cubic, equation. If you choose a second, or higher, order equation, the graph of Y vs. X will be curved, depending on the choice of a_1, a_2, a_3, a_4 .... The polynomial equation above takes the form of a 12^{th} order polynomial, where a_1 .....a_{12} are the coefficients of the polynomial, a_0 is the constant coefficient. In terms of the Pz graph it is the Pz value e.g. Pz upper = 0.117, this is the unknown value that needs to be derived. x is the constant e.g. Zupper = 1.19. Therefore what the polynomial is doing is trying to estimate the Pz value e.g. if the Z value is 1.19 what will be the Pz?

To derive the values of x the author will use the least squares method. Least squares is a mathematical optimisation technique which, when given a series of measured data, attempts to find a function which closely approximates the data (a *"best fit")*. It attempts to minimise the sum of the squares of the ordinate differences (called residuals) between points generated by the function and corresponding points in the data, this technique is commonly used in curve fitting.

It would be too time consuming to calculate this by hand considering the large number of iterations required to find an optimised fit. The author has decided to use Microsoft Excel to perform the fitting calculation. Microsoft Excel has a function "LINEST" which calculates the coefficients of the polynomial to the required order, in this case 12.

To help understand this function the author has used the Z value of 0.00, from the table in appendix 3 the Pz value will by 0.500. The function "LINEST" has the syntax LINEST(y,x^{1,2,3,4,5,6,7,8,9,10,11,12}) where x and y represent the data sets.

This performs a mathematical optimisation technique, known as a least squares best fit, where the output from this function is the array (a_{12},a_{11},a_{10},a_9,a_8,a_7,a_6,a_5,a_4,a_3,a_2,a_1,a_0)

The Microsoft Excel function "INDEX" is used to extract the individual coefficients from the array.

INDEX(LINEST…,1,1) extracts a_{12}

INDEX(LINEST…,1,2) extracts a_{11}

INDEX(LINEST…,1,3) extracts a_{10}

INDEX(LINEST…,1,4) extracts a_9

INDEX(LINEST…,1,5) extracts a_8

INDEX(LINEST…,1,6) extracts a_7

INDEX(LINEST…,1,7) extracts a_6

INDEX(LINEST…,1,8) extracts a_5

INDEX(LINEST…,1,9) extracts a_4

INDEX(LINEST…,1,10) extracts a_3

INDEX(LINEST…,1,11) extracts a_2

INDEX(LINEST…,1,12) extracts a_1

INDEX(LINEST…,1,13) extracts a_0

$$y = (c12*x^{12}) + (c11*x^{11}) + (c10*x^{10}) + (c9*x^{9}) + (c8*x^{8}) + (c7*x^{7}) + (c6*x^{6}) + (c5*x^{5}) + (c4*x^{4}) + (c3*x^{3}) + (c2*x^{2}) + (c1*x^{1}) + b$$

This is the 12th order polynomial that will calculate the Pz value, y, where x is the Z value the remaining values c12 to c1 and b can be derived from the Microsoft Excel formulas below:

c12: =INDEX(LINEST(y,x$^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1)

c12 = -3.4672E-07

c11: =INDEX(LINEST(y,x$^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,2)

c11 = 1.65352E-06

c10: =INDEX(LINEST(y,$x\{^{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,3)

c10 = 3.20644E-05

c9: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,4)

c9 = -0.00037153

c8: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,5)

c8 = 0.001758436

c7: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,6)

c7 = -0.005325067

c6: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,7)

c6 = 0.013836604

c5: =INDEX(LINEST(y,$x\{^{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,8)

c5 = -0.027614137

c4: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,9)

c4 = 0.013544079

c3: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,10)

c3 = 0.06042706

c2: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,11)

c2 = 0.00143269

c1: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,12)

c1 = -0.399052655

b: =INDEX(LINEST(y,$x^{\{1,2,3,4,5,6,7,8,9,10,11,12\}}$),1,13)

b = 0.499991771

y = (-3.4672E-07*x^{12}) + (1.65352E-06*x^{11}) + (3.20644E-05*x^{10}) + (-0.00037153*x^{9}) + (0.001758436*x^{8}) + (-0.005325067*x^{7}) + (0.013836604*x^{6}) + (-0.027614137*x^{5}) +

$(0.013544079*x^{4}) + (0.06042706*x^{3}) + (0.00143269*x^{2}) + (-0.399052655*x^{1}) +$

0.499991771

This formula will be added to the design evaluation tool to replace the table in appendix 3 for the calculation of defects for the key features. To validate the accuracy of the formula, appendix 4 has been produced showing an additional column highlighting the comparison. In addition to the graph in figure 5.14 the calculated formula is added to this in figure 5.15. The blue line is the original line produced from the table in appendix 3. The yellow line indicates the figures that have been calculated from the 12th order polynomial; this highlights the comparison of the two sets for figures and shows how similar they are. This indicates the stability of the design evaluation tool when calculating the potential defects of the product.

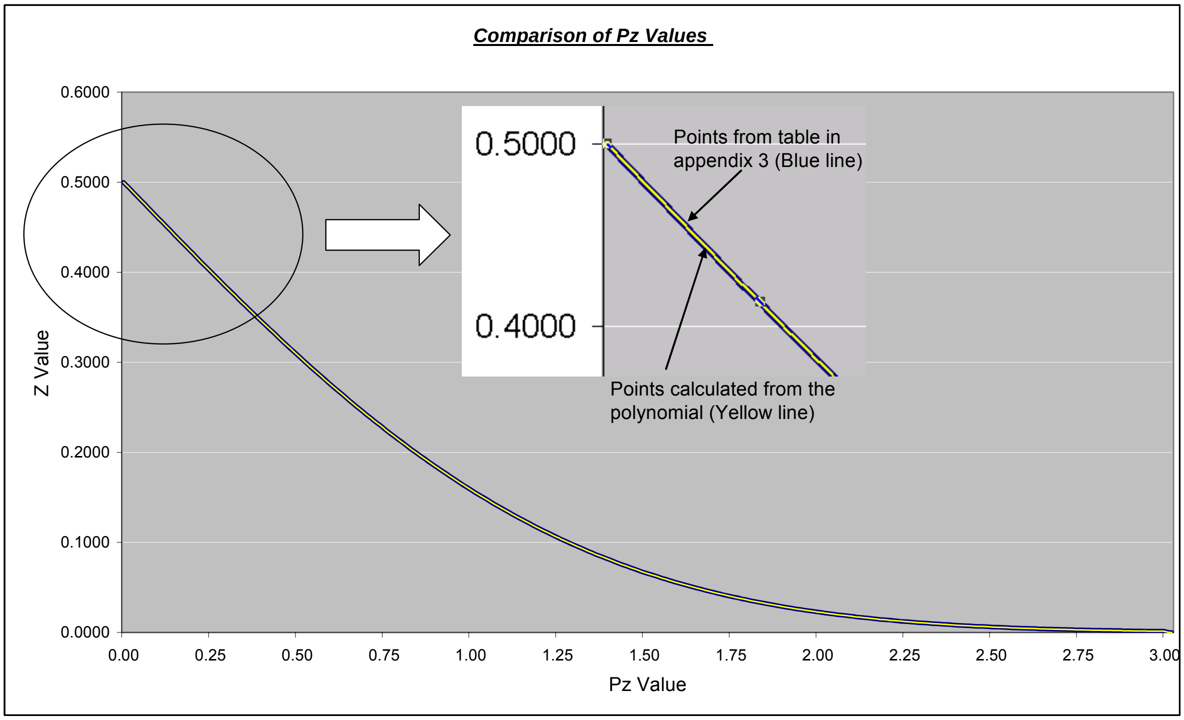


Figure 5.15 – A graphical representation of a comparison between the figures from the Pz value in appendix 3 and those calculated from the 12th order polynomial.

Appendix 4 highlights minimal difference between the two Pz values, however there is a minimal amount of variation. Using the previous Pz upper and Pz lower values the author highlights the difference. Using the Z values, the table in appendix 3 calculated the following;

Pz upper = 0.117 x 100 = 11.7% of defects.

Pz lower = 0.1949 x 100 = 19.4% of defects.

If these Pz values are calculated using the 12th order polynomial in the design evaluation tool there will be minimal differences;

Pz upper = 0.117 x 100 = 11.62% of defects, a deduction of 0.08%

Pz lower = 0.1949 x 100 = 19.28% of defects, a deduction of 0.12%

The author's conclusion of these minimal differences is that they will have little or no effect on the design evaluation tools outputs.

The total amount of points outside of the design tolerance, between upper and lower design specifications, for surface machining of a rib would therefore be 30.9%

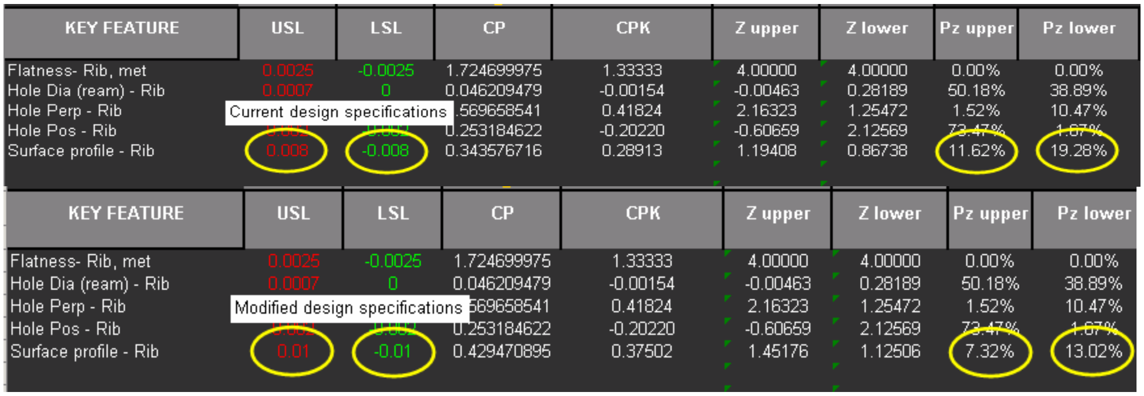
This highlights its tangibility when comparing the design and the manufacturing process capability data. With this, the design for manufacture engineer could propose an increase of the design tolerance, as in the previous example, from +/- 0.008" to +/- 0.010". Then trying to justify these changes, the engineer would have tangible data to enforce a *"best guest"* engineering judgement.

The increase in design tolerance would reduce the amount of defects for the key feature by;

Pz upper = 7.32% of defects

Pz lower = 13.02% of defects

The overall reduction of defects for the upper and lower design limits by increasing the design specification limits by +/- 0.002” would be a reduction of 10.56%. Figure 5.16 highlights this in the design evaluation model.



Current design specifications

KEY FEATURE	USL	LSL	CP	CPK	Z upper	Z lower	Pz upper	Pz lower
Flatness- Rib, met	0.0025	-0.0025	1.724699975	1.33333	4.00000	4.00000	0.00%	0.00%
Hole Dia (ream) - Rib	0.0007	0	0.046209479	-0.00154	-0.00463	0.28189	50.18%	38.89%
Hole Perp - Rib			.569658541	0.41824	2.16323	1.25472	1.52%	10.47%
Hole Pos - Rib	0.002	-0.002	0.253184622	-0.20220	-0.60659	2.12569	73.47%	1.67%
Surface profile - Rib	0.008	-0.008	0.343576716	0.28913	1.19408	0.86738	11.62%	19.28%

Modified design specifications

KEY FEATURE	USL	LSL	CP	CPK	Z upper	Z lower	Pz upper	Pz lower
Flatness- Rib, met	0.0025	-0.0025	1.724699975	1.33333	4.00000	4.00000	0.00%	0.00%
Hole Dia (ream) - Rib	0.0007	0	0.046209479	-0.00154	-0.00463	0.28189	50.18%	38.89%
Hole Perp - Rib			569658541	0.41824	2.16323	1.25472	1.52%	10.47%
Hole Pos - Rib	0.002	-0.002	0.253184622	-0.20220	-0.60659	2.12569	73.47%	1.67%
Surface profile - Rib	0.01	-0.01	0.429470895	0.37502	1.45176	1.12506	7.32%	13.02%

Figure 5.16 – Design Evaluation Tool, Pz values

In general, the reductions in deviations for the increase in tolerance are relatively small. To help better understand the defects there are a number of general terms used; defects per million opportunities (DPMO) and defects per unit (DPU). These can be calculated using the current data.

$$\text{DPMO} = (\text{Pz upper} + \text{Pz lower}) \times 1000000$$

$$\text{DPMO} = (0.1928 + 0.1162) \times 1000000$$

$$\text{DPMO} = 308954$$

If the tolerance is increased to +/- 0.010 then the DPMO would decrease to:

$$\text{DPMO} = (0.0732084 + 0.1302115) \times 1000000$$

DPMO = 203420

A reduction of 105534 defects

Defects per unit is the potential number of defects that may occur for each product produced, the formula for this is;

DPU = (Pz upper + Pz lower) x OFD

Opportunities for defect (OFD) are the number of opportunities that a defect can occur on a product. In this case of a surface profile tolerance on a component it is the number of times the key feature appears on the product. In this case, where we are looking at ribs it will be twice for the upper and lower surfaces.

DPU = (0.1928 + 0.1162) x 2

DPU = 0.6179

If the tolerance is increased to +/- 0.010 then the DPU would decrease to:

DPU = (0.0732084 + 0.1302115) x 2

DPU = 0.4068

From the statistical data calculated above further data can be calculated to evaluate the output of the process. First time yield (yield) shows the proportion of units that, on average, go through manufacturing first time without defects. This is a widely used quality indices, use to establish how in control a product is. The formula below is used to calculate the key features yield:

$$e^{-dpu}$$

e = 2.718

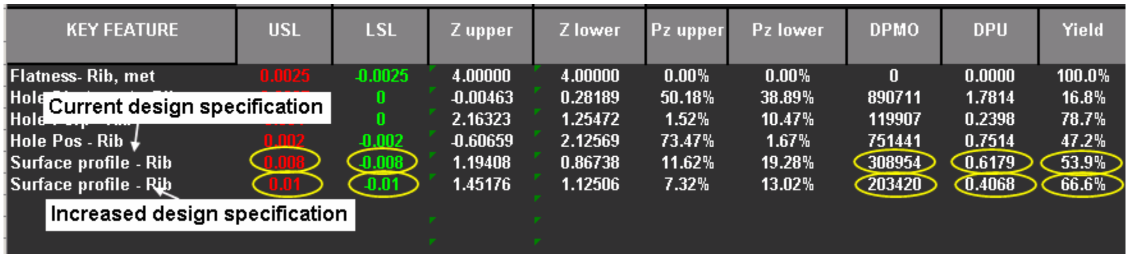
This is a mathematical constant and is the base of the natural logarithm.
DPU = 0.6179

$$\text{Yield} = 0.539 \times 100 = 53.9\%$$

As previous, if the tolerance is increased to +/- 0.010 then the yield would increase to:

$$\text{Yield} = 66.6\%$$

Figure 5.17 highlights the above calculation in the design evaluation tool.



KEY FEATURE	USL	LSL	Z upper	Z lower	Pz upper	Pz lower	DPMO	DPU	Yield
Flatness- Rib, met	0.0025	-0.0025	4.00000	4.00000	0.00%	0.00%	0	0.0000	100.0%
Hole [illegible]	[illegible]	0	-0.00463	0.28189	50.18%	38.89%	890711	1.7814	16.8%
Hole [illegible]	[illegible]	0	2.16323	1.25472	1.52%	10.47%	119907	0.2398	78.7%
Hole Pos - Rib	0.002	-0.002	-0.60659	2.12569	73.47%	1.67%	751441	0.7514	47.2%
Surface profile - Rib	0.008	-0.008	1.19408	0.86738	11.62%	19.28%	308954	0.6179	53.9%
Surface profile - Rib	0.01	-0.01	1.45176	1.12506	7.32%	13.02%	203420	0.4068	66.6%

Figure 5.17 – Design evaluation tool, DPMO, DPU, Yield

5.5.5 Cost calculation of defects in relation to the design

The design evaluation tool uses process capability data to establish the robustness of the design, using process capability indices, discussed previously. It has been discussed that there is a need for manufacturing engineers to have more tangible data to measure the manufacturability to the customer requirements. With this in mind the design evaluation tool develops by introducing costs, translating the complex CP & CPK values into more tangible supportive data to aid the direction of the design ensuring the customer requirements and predetermined costs can be met prior to manufacture and detail design stages commencing.

The design evaluation tool looks at two main areas of cost; first the concession and non conformance and secondly the repair cost to bring the product back to within the designed or concession design standard.

Concession cost is the related engineering cost in bringing the defected product back to an acceptable standard that can ensure its use. In many manufacturing environments such as automobile manufacture most of the defective products will be scrapped as the engineering costs to rework the product would exceed the cost of the product itself, even with larger products such as cylinder heads etc. However, in airframe manufacture, many components have a high monetary value e.g. the main structural frames in an aircraft structure may cost in excess of £100,000. It is not only the physical costs of products but the traceability paperwork also has a large contribution to the overall cost. Major products on an aircraft have to maintain traceability, where all the data such as inspection, material batch numbers, protective treatments etc. have to be tagged to the product and maintained for the life of the aircraft.

Deciding how to repair a defective product involves various engineering disciplines. Design engineering need to model the defective component, looking how it will affect the design and the overall assembly. Stress engineers need to recalculate and assess the loads that will be affected by the defects on the product. Assembly manufacturing engineers need to assess the potential issues which may occur on the assembly build, due to the defective products. There are other engineering disciplines that may need to be involved in the assessment. On completion of the concession, the quality team need to establish corrective action plans to ensure that the defect does not reoccur.

The design evaluation tool estimates the potential of a concession, therefore allocating this to the overall defects cost. As highlighted previously, concession costs can be a large part of the overall defect cost. Defects per unit (DPU) are used to calculate the probability of a concession, as illustrated in figure 5.17. A sensitivity marker is set to control the probability of the concession:

The DPU of the surface profile for metallic ribs is 0.618, there will always be a DPU value for the key features. It is therefore up to the organisation to set the level of the sensitivity value, e.g. a sensitivity value of 0.5 would include the concession cost in the overall defect cost; however a sensitivity of 0.7 would not include this in the overall defect cost. An organisation can establish this value by reviewing the past concession rates in their business.

The second source of defect cost is the cost to rework the product to ensure the incorrect feature is acceptable to the design requirements enabling the product to be used on the aircraft. To calculate these costs the design evaluation tool calculates the probability of the defect and whether the probability of the defect exceeds the USL or the LSL, allocating a cost to the appropriate defect area. To explain this area more clearly an example of hole diameter can be used:

The design specification for a hole in a component is a diameter tolerance of 6mm + 0.1mm / - 0.000mm. In terms of a defect the hole could be under the design specification; say 5.8mm, or over the design specification; say 6.2mm. These two potential scenarios would create very different issues to the performance of the product. The under size hole would produce an issue on assembly that the fastener could not be installed. If the hole were to be oversized then there would be a loose fit fastener in the structure, this could reduce the amount of load that would be carried through the joint, e.g. there would have to be some deformation before the fastener would carry load and fretting of the fastener would also be a potential issue. Taking these into consideration the hole would have to be reworked back to the designed tolerance and there would be different rework processes for the two scenarios.

The undersize hole rework would be to open up the hole with a tool to achieve the design standard, this would introduce little cost to the product. If the hole was oversize the hole may have to be opened up to a larger size and a bush or sleeve fitted to ensure the designed tolerance is achieved, this would substantially increase the cost to the product than the previous rework process.

Taking this into consideration it would not be acceptable for the design evaluation tool to associate a single cost to a defect. This would give a misrepresentation of the actual rework costs. With this in mind, the design evaluation tool calculates the highest probability of the defect, whether it is exceeding the USL or the LSL. Figure 5.18 illustrates this;

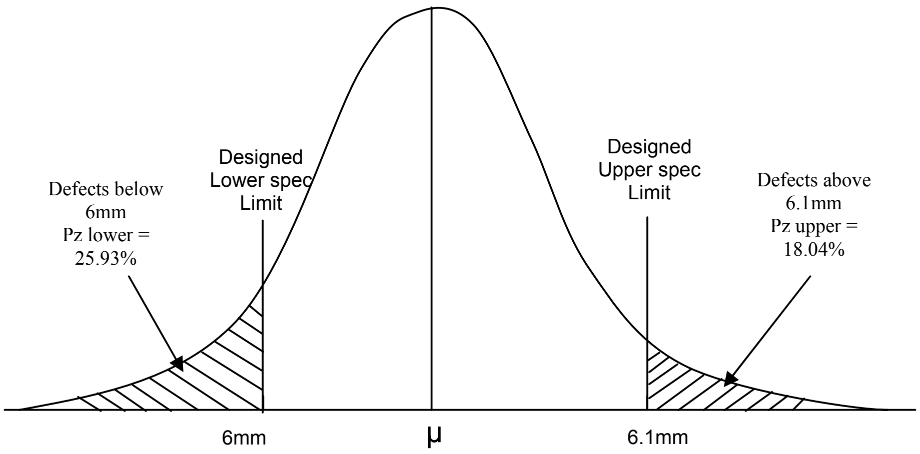


Figure 5.18 – Selecting defect costs for a hole diameter

Using the Pz values from key feature hole diameter for metallic ribs, as illustrated in figure 5.18, the Pz values indicate that there is a higher probability that manufacturing a hole with the current process capability in place the hole with be undersize. Therefore, the design evaluation tool will allocate a cost to open the hole diameter to within design limits.

The cost is calculated by the amount of time it takes to rework the feature. In the above example the time to repair for over sized hole would be the time it takes to open up the hole (0.75 hrs), Counter bore for bush (0.250 hrs), fit the bush (0.250hrs), there will be an additional time of (0.5hrs) for manufacture of bush therefore the total time being 1.5 hours. For an undersize hole, the hole would require opening up to within the design limits, the time allocated to this is 0.333 hrs, and these hours are to be multiplied by the appropriate hourly rate in pounds for the specific process.

Figure 5.18 shows the Pz value for an undersize hole (25.93%) and an oversize hole (18.04%). Therefore to ensure that the design evaluation tool predicts an accurate rework cost it has been programmed to select the highest Pz value to apply the rework cost, in the above example it would be 0.333 x £50 = £16.65. Each key feature has a time associated to the repair of a defect outside the USL and LSL. This is shown in appendix 2.

The author has identified a "*grey area*" as to whether a cost should be allocated in the design evaluation tool. This area has been addressed by the introduction sensitivity makers to control the probability of concessions, rework costs and main contributors; these have been highlighted in figures 5.8 and 5.9. The author has discussed this in more detail in Section 5.5.5.

5.6 Conclusion

In summary of the present chapter the author has presented a number of solutions to the gaps identified in the current academic work, identified in chapter 4. The author discusses the importance of the selection of the environment of which the design life-cycle operates in. A novel selection tool is discussed, after analysis from senior industrial experts from the aircraft industry it was concluded that for high complexity low volume products, such as aircraft, a concurrent environment would be the most effective.

The author introduces a novel design life-cycle that enables a structured approach to the design of high complex products such as aircraft. This structured approach helps control the large amount of technical data that is required in this environment. The core of the process flow is based on seven phases; requirements definition, conceptual design, embodiment design, detail design, production planning, manufacturing, and maintenance and support. These distinct steps help structure the maturing design. To control the complexity of the data mass, three main drivers are introduced; requirements definition, review gates and a decision maker. After these phases and drivers had been developed by the author, it became apparent that is was difficult for manufacturing engineers to introduce tangible data at the review gates. This derived the main area of the research by presenting a solution to this problem.

The literature survey highlighted the need for manufacturing engineering to have the ability to assess the design for manufacturability. The author introduces a solution to this gap in the existing academic work by the introduction of a design evaluation model. The key characteristics are selected from the design and using manufacturing process capability data, they are mathematically analysed to predict the additional costs that will be incurred by the business if the design moves into manufacture. Using the proposed design life-cycle, each discipline has to pass a review gate to enable a reduction of risk through the design life-cycle. Engineering disciplines like weight engineering and structure analysis engineering can offer this information, however manufacturing engineering has not been able to introduce tangible data in the same way as our disciplines. This chapter offers a solution to this by using the model to develop a design evaluation tool measuring the manufacturability of the design during the design phase. The outputs from the tool aid the decision maker to decide whether to allow the design to pass through the review gates by validating the products manufacturability to the customer requirements. This tool introduced by the author will also enable a comparison of the design from various engineers, highlighting how well the designer has thought about the manufacturability and cost of the product. The tool will assist in establishing best practice through the design life-cycle.

Chapter 6 Validation and Test

6.1 Introduction

The chapter discusses the three experimental phases which have been used to validate and test the design evaluation tool introduced by the author. The chapter starts with the justification of the choice of an experimental technique building upon the discussion of research methodology given in chapter 3. Within an industry of low volume high complexity, such as aircraft design and manufacture, it is difficult to truly measure the effect on the product. This, in the main, is due to the length of the life-cycle of the product. The total life span of an aircraft, from initial design phase to manufacture takes many years, even decades, to complete. Even if a design evaluation tool was to be validated throughout the complete life-cycle of the product, changes to the design would be unlikely as any major design changes, particularly airframe, would have to go through stringent re-certification requirements prior to any adoption of change to the design of the product. This is a fundamental problem in aircraft design research. With this taken into consideration the author has carefully selected three experimental phases to verify the research.

As discussed in Chapter 3 the experimental phases are intended to validate the effect the design evaluation tool has on the current design of aircraft. The first experimental phase, Validation of Process on a Theoretical study of an Aircraft Tail, was to ensure that the various inputs to the design evaluation tool are correctly calculated to produce valid output data from the tool. The second experimental phase, Design Evaluation of an Aircraft Structure Currently in Production, was used as an aid in decision making as to what type of structure should be designed to enable a different manufacturing process. The third, Design Evaluation and comparison of an Aircraft Structure Currently in Production, was structured to produce a design evaluation model of an existing design and compare the predicted results with the actual results seen in manufacturing. The benefits from including the experimental phases in the research were expected to be as follows:

- Enhanced industrial experience. Although the author has extensive experience in the design and manufacture of aircraft, over twenty two years, it has enabled him to expand *"real-world"* experience into a wide range of disciplines involved in the area of research.
- Access to a variety of products and data within this industrial area. This enhanced the author's ability to select robust experimental phases which validate the research.
- Validation. The experimental phases help to prove or disprove the hypotheses of the thesis and answer the research questions from a broader point of view.
- Access to experts in the field. Within this environment there are many complexities that can occur; these cover a wide range of disciplines. During the experimental phases the author will have the opportunity to discuss issues with experts in the relevant field.

6.2 Experimental Phase 1

Validation of the Process on a Theoretical Study of an Aircraft Tail

6.2.1 Introduction

The background to the proposed design evaluation has been discussed in chapter 5 where the combination of process capability data, design key characteristics and the author's collection of mathematical formulas work together to generate a defect cost and other data to establish the manufacturability of the design. Clearly if each key characteristic had to be manually compared to the process capability data, the time it would take to evaluate would be excessive.

To help in analysing the data, the formula, process capability data and the product key characteristics were loaded into Microsoft Excel to produce the design evaluation tool. To ensure the validation of the results prior to engaging in further experimental phases, the author produced this theoretical experimental phase. This was based on a design of a simplified tail plane from an aircraft. The author designed the product in 3D to closely simulate a product design, shown in figure 6.1.

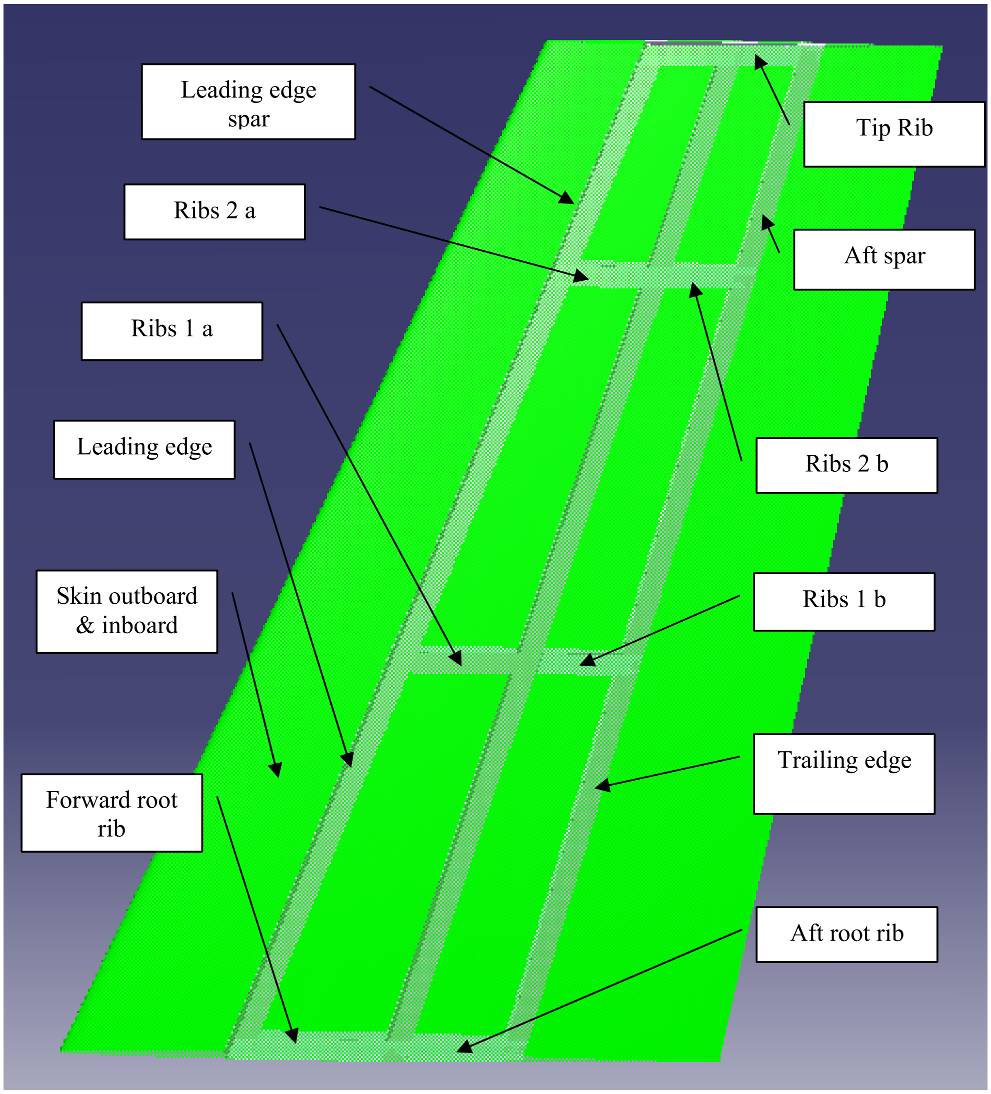


Figure 6.1 – Theoretical Design of an Aircraft Tail

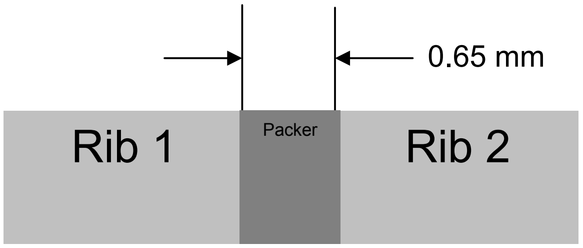
Appendix 5 shows further detail for each individual component and how they are integrated within the assembly.

6.2.2 Detail of the theoretical design.

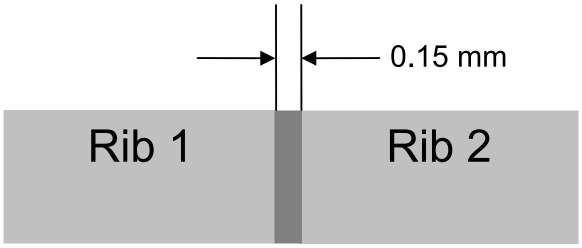
The assembly has been designed to simulate a major sub-assembly of an aircraft. The structure of the assembly is made up of spars and ribs that are assembled between two skins. The materials that are generally used in aircraft design are titanium, aluminium and composite material such as carbon fibre.

The individual parts will be assembled in an assembly fixture, located on the predetermined key characteristics. These features or datums are controlled by the application of tolerances applied to the 3D model in the detail design phase of the design life-cycle. This will ensure that the components can be installed in the assembly. Each part has a tolerance, for example +/- 0.25 mm, which means that when located in the assembly fixture the two parts can have a gap of between 0.5 mm and an interference of 0.5 mm. With this in mind, if both components were manufactured within the designed tolerance there would be a high chance that they would not fit together on assembly. Therefore, the design will have to ensure that there is a physical gap modelled to ensure fitment. For example the modelled gap condition would be 0.65 mm; 0.50 mm for the component's variation and 0.15 mm for variation in the location of the parts in the jig

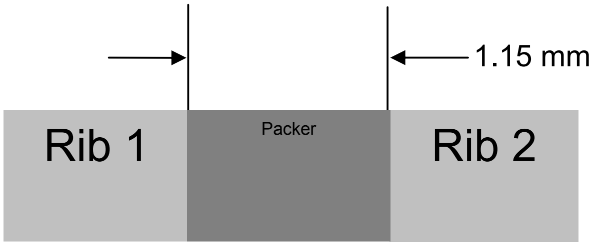
This is explained further in figure 6.2



If both parts were manufactured at nominal and there was no jig location error incurred the gap would be 0.65 mm. The gap would be filled with a packer and then drilled / fastened



If both parts were manufactured to their top limit and there was no jig location error incurred the gap would be 0.15 mm. The gap would be filled with a packer and then drilled / fastened.



If both parts were manufactured on their bottom limit and there was no jig location error incurred the gap would be 1.15 mm. The gap would be filled with a packer and then drilled / fastened.

Figure 6.2 – Designed gap condition for the location of components.

Each joint in the structure will be designed in this manner.

To fix the joint into position a joining bracket has been designed to ensure that the joints are secure and can withstand the predicted load determined by the structural engineers. The joint configuration is illustrated in figure 6.3. The number of fasteners will be dependent on the load that the joint will have. The reasons for this joint configuration was for a reduction in the complexity of the design, reduction in packers, less complex detail components to manufacture and fewer key features.

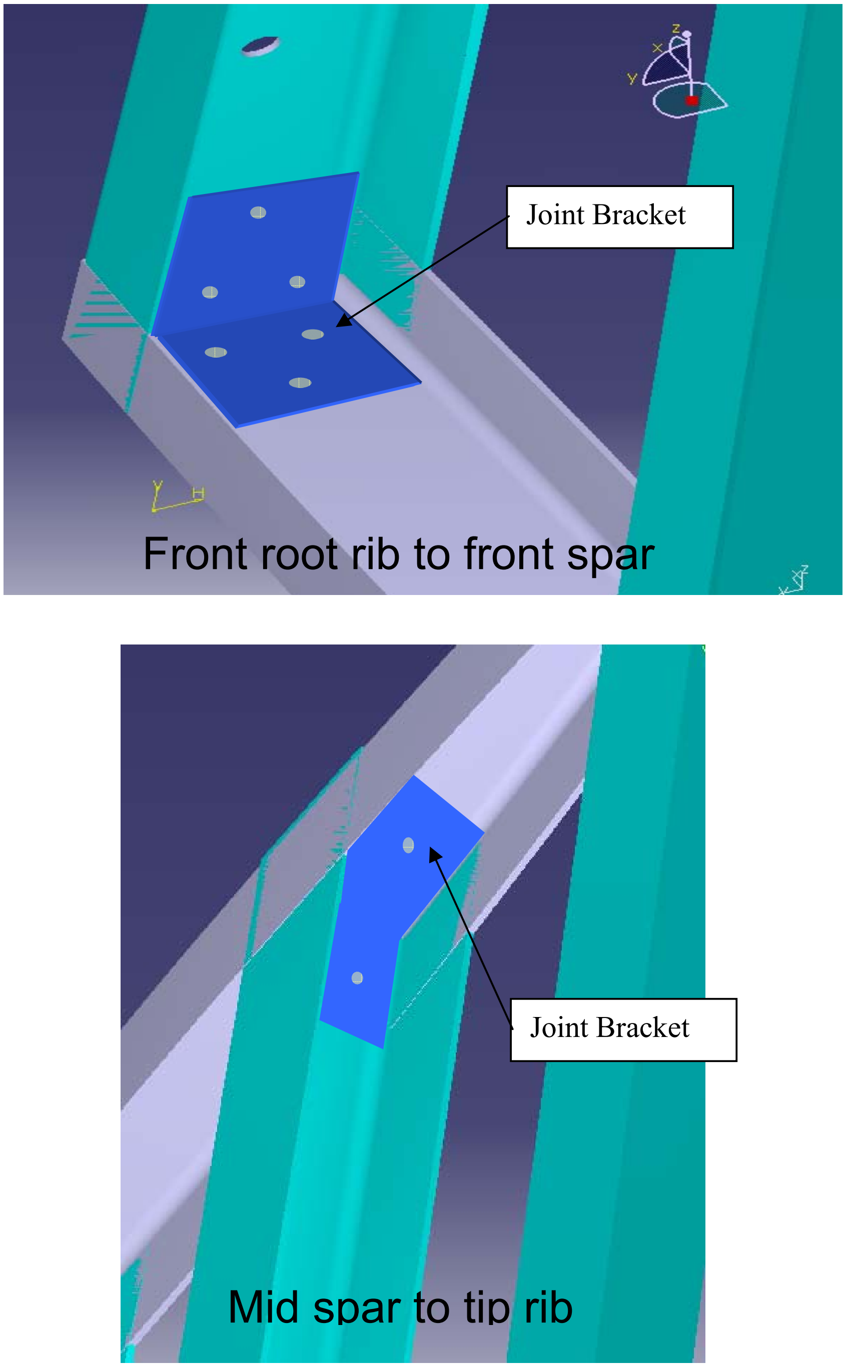


Figure 6.3 – Designed Joint Configuration

The assembly is fastened together using tension fasteners between each joint and the skins are substructure. The fasteners are a two piece fastener system that falls into two categories;

- Self torque – This fastener system has an integrated torque system that ensures when the fastener is being installed only a specified torque will be applied.
- Manual torque – this is where a torque wrench has to be applied to provide the specified torque to the fastener

The detail of where the fasteners are installed and examples of the various types are highlighted in appendix 5, which summarises to:

Joints within the substructure

Self torque = 46

Manual torque = 6

Fasteners between the skins are substructure

Outboard skin, self torque = 133

Inboard skin, self torque bolts = 133 and 133 retained nuts system.

6.2.3 Population of the Design Evaluation Tool

The design evaluation tool has five main inputs, discussed in detail in chapter 5;

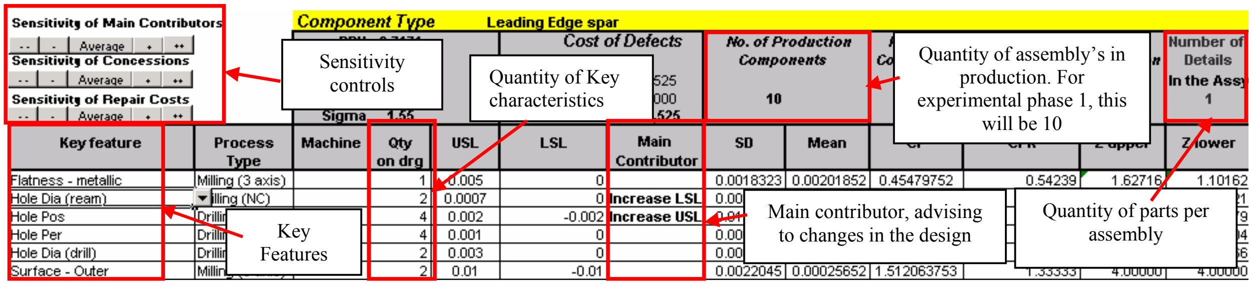
- Process Capability Data – This is pre-loaded into the tool and should be continually updated.
- Design Key Characteristics – These are identified key features and processes that for which variation significantly affects product performance, quality, cost or safety.

- Cost data – Cost data is pre-loaded into the tool, these are repair times that are associated with defects that may occur in manufacturing, shown in detail in appendix 2.
- Tolerances from the key characteristics – Each key feature should have a tolerance that can be measured by the design evaluation tool.
- Quantity of products – the tool needs to know the quantity of product per assembly and the number of assemblies in production

The key characteristics of the proposed design were loaded into the design evaluation tool; these are discussed in more detail in appendix 5. The tool has a menu of KC's that can be selected, or loaded if not present. The following KC's were loaded for each of the components in the design along with quantities and the number of times they occur. The quantity of each product per assembly is also loaded into the tool. Figure 6.4 highlights these inputs

Leading Edge – (1 per assembly)

• Flatness	Quantity 1
• Hole Diameter (reaming process)	Quantity 2
• Hole Position	Quantity 4
• Hole Perpendicularity	Quantity 4
• Hole Diameter (drilling process)	Quantity 2
• Surface Profile	Quantity 2



Key feature		Process Type	Machine	Qty on drg	USL	LSL	Main Contributor	SD	Mean	[illegible]	[illegible]	Z upper	Z lower
Flatness - metallic		Milling (3 axis)		1	0.005	0		0.0018323	0.00201852	0.45479752	0.54239	1.62716	1.10162
Hole Dia (ream)		illing (NC)		2	0.0007	0	Increase LSL	0.00					21
Hole Pos		Drillin		4	0.002	-0.002	Increase USL	0.01					79
Hole Per		Drillin		4	0.001	0		0.00					04
Hole Dia (drill)		Drillin		2	0.003	0		0.00					66
Surface - Outer		Millin		2	0.01	-0.01		0.0022045	0.00025652	1.512063753	1.33333	4.00000	4.00000

Sensitivity controls

Quantity of Key characteristics

Quantity of assembly's in production. For experimental phase 1, this will be 10

Key Features

Main contributor, advising to changes in the design

Quantity of parts per assembly

Figure 6.4 – Inputs required for the Design Evaluation Tool – Experimental phase 1

Mid Spar – (1 per assembly)

Flatness	Quantity 1
Hole Diameter (reaming process)	Quantity 2
Hole Position	Quantity 4
Hole Perpendicularity	Quantity 4
Hole Diameter (drilling process)	Quantity 2
Surface Profile	Quantity 2

Aft Spar (1 per assembly)

Flatness	Quantity 1
Hole Diameter (reaming process)	Quantity 2
Hole Position	Quantity 4
Hole Perpendicularity	Quantity 4
Hole Diameter (drilling process)	Quantity 2
Surface Profile	Quantity 2

Tip Rib (1 per assembly)

Flatness	Quantity 1
Hole Diameter (reaming process)	Quantity 2
Hole Position	Quantity 3
Hole Perpendicularity	Quantity 3
Hole Diameter (drilling process)	Quantity 1
Surface Profile	Quantity 2

Forward Root Rib (1 per assembly)

Flatness	Quantity 1
Hole Diameter (reaming process)	Quantity 2
Hole Position	Quantity 3
Hole Perpendicularity	Quantity 3
Hole Diameter (drilling process)	Quantity 1
Surface Profile	Quantity 2

Aft Root Rib (1 per assembly)

Flatness	Quantity 1
Hole Diameter (reaming process)	Quantity 2
Hole Position	Quantity 3
Hole Perpendicularity	Quantity 3
Hole Diameter (drilling process)	Quantity 1
Surface Profile	Quantity 2

Ribs 1 and 2 (4 per assembly)

Flatness	Quantity 1
Hole Diameter (reaming process)	Quantity 2
Hole Position	Quantity 2
Hole Perpendicularity	Quantity 2
Hole Diameter (drilling process)	Quantity 2
Surface Profile	Quantity 2

Joint Attachment Brackets (12 per assembly)

Flatness	Quantity 1
Hole Diameter (drilling process)	Quantity 6
Hole Diameter (pilot holes)	Quantity 6

Skins (2 per assembly)

Flatness	Quantity 1
Hole Diameter (reaming process)	Quantity 2
Hole Position	Quantity 3
Hole Perpendicularity	Quantity 3
Hole Diameter (drilling process)	Quantity 2
Edge of Part	Quantity 4

The components above are individual parts that are generally machined to achieve the features of the part. To complete the overall product assembly, a number of additional processes are required, these are identified below. The process capability data varies between variation data, and attribute data.

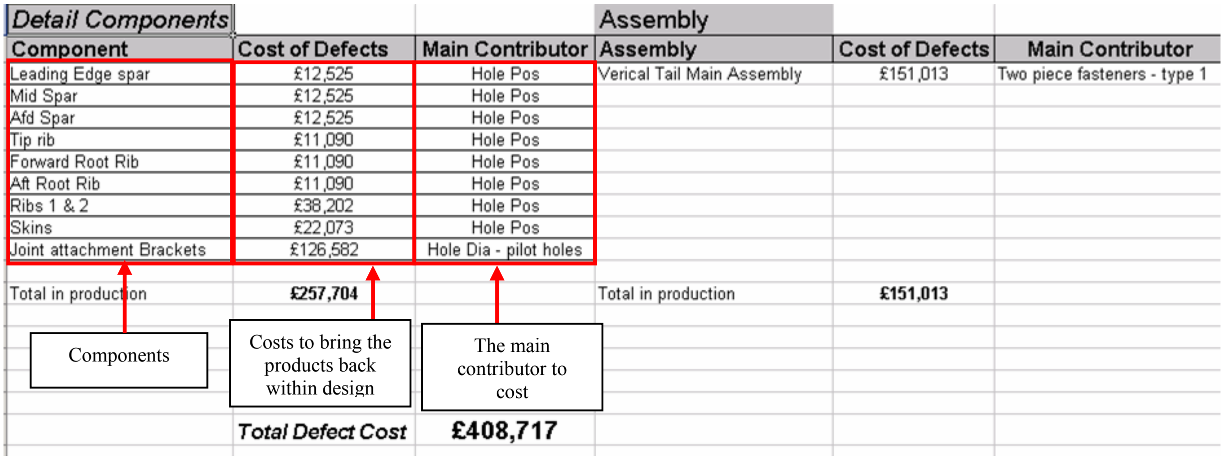
Assembly processes.

• Component installation, type 1 - Jig located	Quantity 10
• Component installation, type 1 - Self located	Quantity 12
• Hole Diameter, controlled drilling process	Quantity 15
• Hole Diameter, manual drilling process	Quantity 28
• Fasteners installation, two piece – self torque	Quantity 179
• Fasteners installation, two piece – manual torque	Quantity 6
• Hole Diameter, automated drilling process	Quantity 266
• Component installation, type 2 - Self located	Quantity 4
• Anchor nut installation, riveted	Quantity 133
• Fastener installation to anchor nuts	Quantity 133

6.2.4 Outputs from the Design Evaluation Tool

Once the inputs were loaded into the design evaluation tool the formula, discussed in chapter 5, converts the design data into various tangible data that measures how manufacturable the proposed design is. There are many outputs from the tool, discussed previously in chapter 5, that other disciplines in the design life-cycle use. The tool calculates the true cost to produce the product to within design specification by estimating the defects, calculating both the rework cost and the redesign costs.

This information is compiled in the tool's summary sheet, shown in figure 6.5



Detail Components			Assembly		
Component	Cost of Defects	Main Contributor	Assembly	Cost of Defects	Main Contributor
Leading Edge spar	£12,525	Hole Pos	Verical Tail Main Assembly	£151,013	Two piece fasteners - type 1
Mid Spar	£12,525	Hole Pos			
Afd Spar	£12,525	Hole Pos			
Tip rib	£11,090	Hole Pos			
Forward Root Rib	£11,090	Hole Pos			
Aft Root Rib	£11,090	Hole Pos			
Ribs 1 & 2	£38,202	Hole Pos			
Skins	£22,073	Hole Pos			
Joint attachment Brackets	£126,582	Hole Dia - pilot holes			
Total in production	**£257,704**		Total in production	**£151,013**	
	Total Defect Cost	**£408,717**			

Components

Costs to bring the products back within design

The main contributor to cost

Figure 6.5 – Summary Sheet – Experimental phase 1

6.2.5 Validation of Results

The design evaluation sheet concludes the analysis into a summary sheet which highlights the main areas of the additional cost if the proposed design were to enter manufacture.

The design evaluation tool estimates any additional costs to the business if the proposed design were to be manufactured, other than those of material and manufacture.

The main contributor to the defect costs within this experimental phase is related to the manufacture of holes within the design limit, with every component being a main contributor to cost. These types of defects could either be due to weak manufacturing capability or the ability to collect this data (inspection).

The largest contributor to defect costs is the joint attachment brackets, contributing over 49% of the overall substructures defects costs. Looking at it in more detail, the author's view is that the large quantity of joint brackets (12) is increasing the opportunity for defects.

The assembly process introduces over 43% to the overall cost of defects, with the self torque fasteners contributing to the majority of this.

The intention is to introduce these results into the design life-cycle to help the decision maker decide whether the design should progress to the next phase. It would be clear to most engineering leads that this scale of excessive cost could not be absorbed into a business. Therefore, further studies should be introduced to reduce them. For the purpose of this research these will be referred to as trade studies, involving most of the engineering disciplines in the design life-cycle.

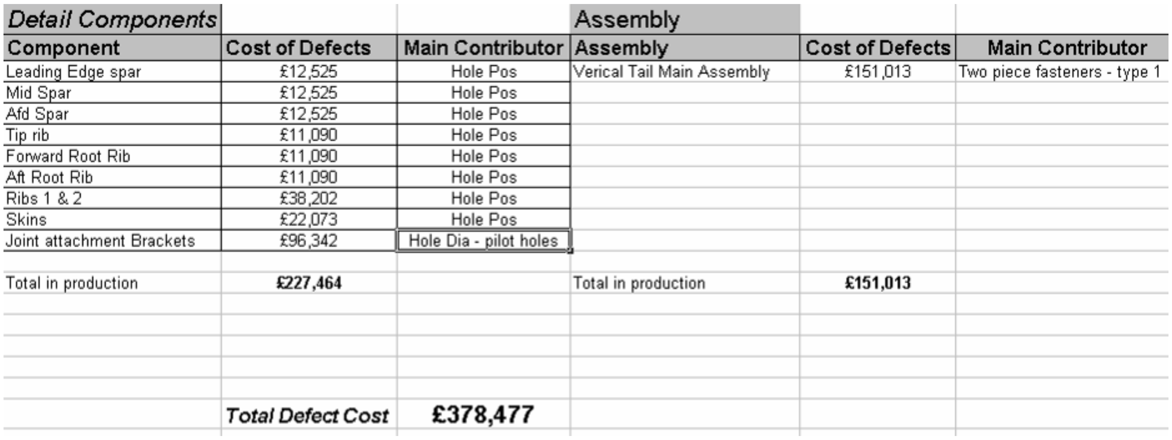
A manufacturing engineer can look in more detail at the design evaluation to establish the key areas that are contributing to this unacceptable cost. Each area needs to be carefully looked at as there are a number of potential areas that could help resolve the additional cost.

A major contributor is hole position and hole diameter (ream), if the tolerance of these were to be increased it would have an effect on the assembly process. Generally, high tolerance holes produce the datum of the component as discussed previously, and illustrated in appendix 5. These datums position the individual components on assembly. If the designed tolerance were to be increased, allowing the holes to be larger, it would increase the likelihood of the components not fitting on assembly. Therefore in this case it would not be feasible to increase the tolerance of these key features. The design team will have to look at increasing the manufacturing capability to reduce the defect costs or try to manage the cost within the business.

6.2.5.1 Trade Study 1

After manufacturing engineering analysed the results from the design evaluation tool it was clear that the joint attachment brackets are the largest contributors to cost for the substructure components. The design evaluation tool has calculated that this is due to the positional tolerance of the pilot holes. Unlike the datum hole tolerances this tolerance could be increased as the holes are not used to position the components, but simply to transfer the holes into the mating substructure. Therefore there would be benefit in design engineering increasing this tolerance.

In this case, design could double the original design tolerance with minimal effect to the product. A simple amendment to the design tolerance in the design evaluation tool will give an instantaneous reduction in defect cost, as shown in figure 6.6 below.



Detail Components			Assembly		
Component	**Cost of Defects**	**Main Contributor**	**Assembly**	**Cost of Defects**	**Main Contributor**
Leading Edge spar	£12,525	Hole Pos	Verical Tail Main Assembly	£151,013	Two piece fasteners - type 1
Mid Spar	£12,525	Hole Pos			
Afd Spar	£12,525	Hole Pos			
Tip rib	£11,090	Hole Pos			
Forward Root Rib	£11,090	Hole Pos			
Aft Root Rib	£11,090	Hole Pos			
Ribs 1 & 2	£38,202	Hole Pos			
Skins	£22,073	Hole Pos			
Joint attachment Brackets	£96,342	Hole Dia - pilot holes			
Total in production	**£227,464**		Total in production	**£151,013**	
	Total Defect Cost	**£378,477**			

Figure 6.6 – Summary Sheet Results form Trade Study 1 – Experimental phase 1

Results from this minor design change, result in an overall reduction in cost of over 7%. The largest single contributor to the product cost is the assembly; therefore the manufacturing engineer needs to look in more detail at the assembly section of the tool to propose additional trade studies.

6.2.5.2 Trade Study 2

When trying to reduce costs in the assembly, generally, more fundamental design changes are required than those in trade study 1.

After a detailed analysis of the data a further trade study can be proposed: the introduction of a new configuration of integral cleats into the ribs. This will remove the separate joint attachment brackets and introduce additional features into the substructure components to enable a structural attachment at each joint interface. Not all joint attachment brackets can be eliminated from the design due to access on assembly. A number of brackets will have to remain, particularly the spar to tip rib connection, this is illustrated in figure 6.7.

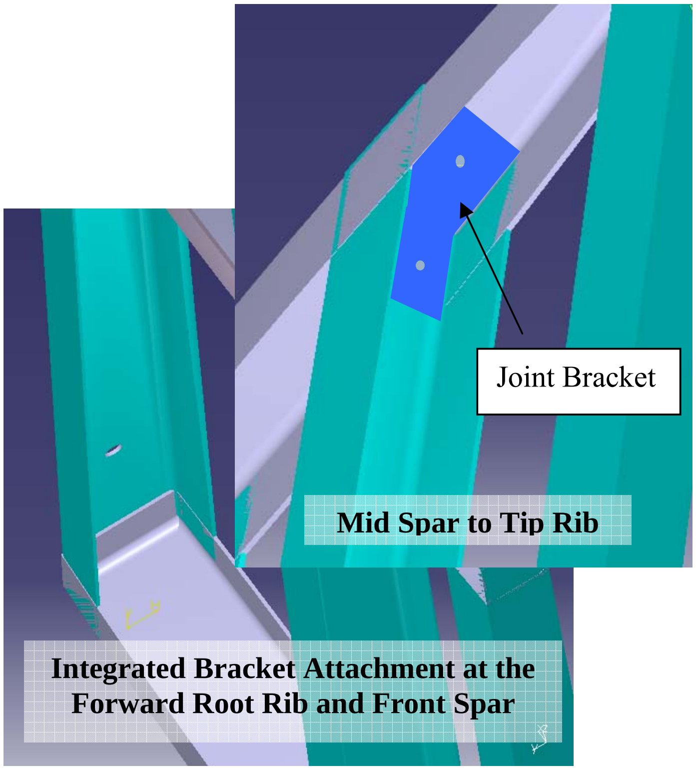


Figure 6.7 – Re-design to Integrated Brackets Trade Study 2 – Experimental phase 1

The introduction of integrated brackets into the substructure will require substantial design if this analysis has taken place prior to the detail design phase. However, analysis by the design evaluation tool can occur in the design life-cycle whenever there is sufficient detail available. Preferably this would occur post detail design phase where the majority of detail designs is produced. If the design process follows the author's proposed design life-cycle, illustrated in figure 5.6, it will help to avoid these potential problems. If a redesign is required later in the design life-cycle, the author's proposed design life-cycle entry points can be used.

The advantages of this trade study are a reduction in components with eleven fewer components and 25 fewer fasteners. In addition the reduction in parts makes the sub-assembly lighter and fewer manual drilling operations on assembly reduces the opportunity for defects.

The disadvantages of the trade study are more key features required on the substructure parts; the detail of these is illustrated in appendix 5 and more complexity has been added to the substructure parts.

These advantages and disadvantages will be analysed by the design evaluation tool to produce an overall view of the design changes, the results of the design evaluation will be instantaneous to the inputs. The changes to the relevant areas in the design evaluation tool are shown in figure 6.8. The detail component has four additional features, surface interface, while the assembly analysis shows both a reduction and addition to its features:

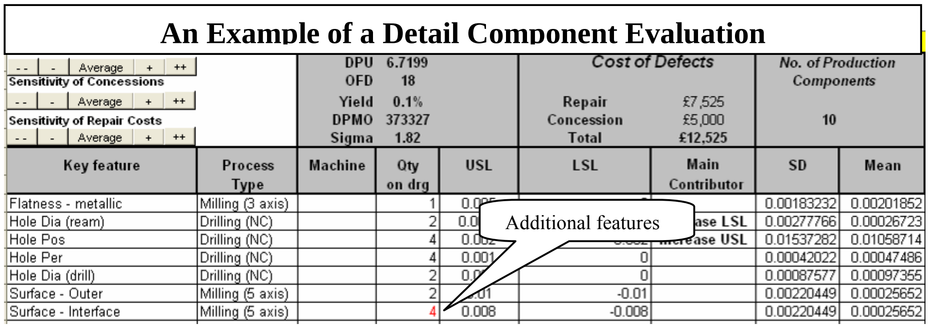
Component Installation Type 2; from a quantity of 12 to 1

Hole Diameter (drill) – Manual; from a quantity of 28 to 12

Two piece fasteners, Type 1; from a quantity of 46 to 21

The additional feature has been added, Shimming Joints, quantity of 4

The results from the addition and subtraction of features caused by the design change are surmised in the summary sheet. This highlights a reduction to the overall defect cost from the initial design is over 33%. The evaluation tool is still highlighting that the assembly is the largest contributor to defect cost. Further design trade studies are required to reduce defect costs.



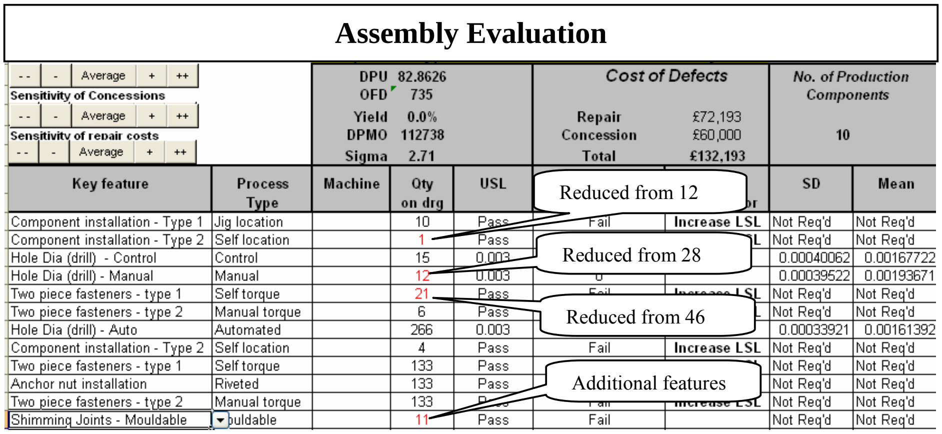
An Example of a Detail Component Evaluation

DPU 6.7199
OFD 18
Yield 0.1%
DPMO 373327
Sigma 1.82

Cost of Defects
Repair £7,525
Concession £5,000
Total £12,525

No. of Production Components 10

Key feature	Process Type	Machine	Qty on drg	USL	LSL	Main Contributor	SD	Mean
Flatness - metallic	Milling (3 axis)		1	0.0			0.00183232	0.00201852
Hole Dia (ream)	Drilling (NC)		2	0.0		ase LSL	0.00277766	0.00026723
Hole Pos	Drilling (NC)		4	0.0			0.01537282	0.01058714
Hole Per	Drilling (NC)		4	0.001	0		0.00042022	0.00047486
Hole Dia (drill)	Drilling (NC)		2	0.0	0		0.00087577	0.00097355
Surface - Outer	Milling (5 axis)		2	.01	-0.01		0.00220449	0.00025652
Surface - Interface	Milling (5 axis)		4	0.008	-0.008		0.00220449	0.00025652



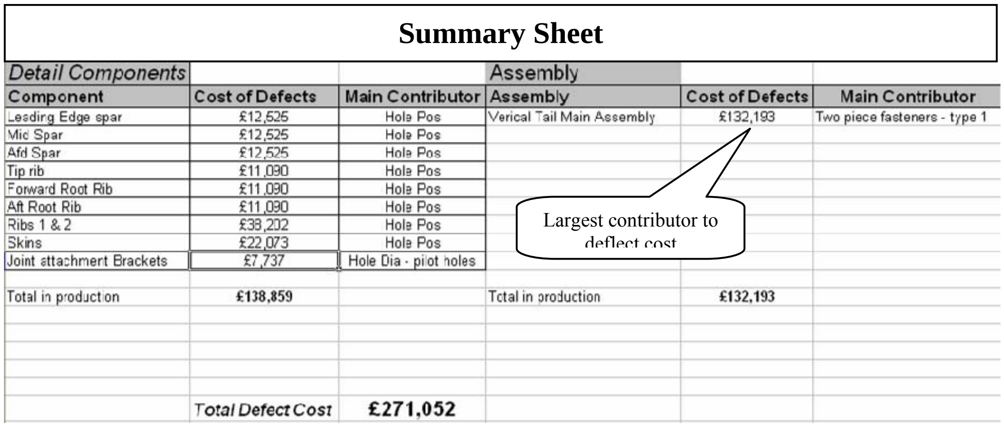
Assembly Evaluation

DPU 82.8626
OFD 735
Yield 0.0%
DPMO 112738
Sigma 2.71

Cost of Defects
Repair £72,193
Concession £60,000
Total £132,193

No. of Production Components 10

Key feature	Process Type	Machine	Qty on drg	USL		or	SD	Mean
Component installation - Type 1	Jig location		10	Pass	Fail	Increase LSL	Not Req'd	Not Req'd
Component installation - Type 2	Self location		1	Pass		L	Not Req'd	Not Req'd
Hole Dia (drill) - Control	Control		15	0.003			0.00040062	0.00167722
Hole Dia (drill) - Manual	Manual		12	0.003	0		0.00039522	0.00193671
Two piece fasteners - type 1	Self torque		21	Pass	Fail	Increase LSL	Not Req'd	Not Req'd
Two piece fasteners - type 2	Manual torque		6	Pass		L	Not Req'd	Not Req'd
Hole Dia (drill) - Auto	Automated		266	0.003			0.00033921	0.00161392
Component installation - Type 2	Self location		4	Pass	Fail	Increase LSL	Not Req'd	Not Req'd
Two piece fasteners - type 1	Self torque		133	Pass		L	Not Req'd	Not Req'd
Anchor nut installation	Riveted		133	Pass			Not Req'd	Not Req'd
Two piece fasteners - type 2	Manual torque		133	Pass	Fail	Increase LSL	Not Req'd	Not Req'd
Shimming Joints - Mouldable	uldable		11	Pass	Fail		Not Req'd	Not Req'd



Summary Sheet

Detail Components			Assembly		
Component	Cost of Defects	Main Contributor	Assembly	Cost of Defects	Main Contributor
Leading Edge spar	£12,525	Hole Pos	Verical Tail Main Assembly	£132,193	Two piece fasteners - type 1
Mid Spar	£12,525	Hole Pos			
Afd Spar	£12,525	Hole Pos			
Tip rib	£11,090	Hole Pos			
Forward Root Rib	£11,090	Hole Pos			
Aft Root Rib	£11,090	Hole Pos			
Ribs 1 & 2	£38,202	Hole Pos			
Skins	£22,073	Hole Pos			
Joint attachment Brackets	£7,737	Hole Dia - pilot holes			
Total in production	**£138,859**		Total in production	**£132,193**	
	Total Defect Cost	**£271,052**			

Figure 6.8 – Results of the Re-design Trade Study 2 – Experimental Phase 1

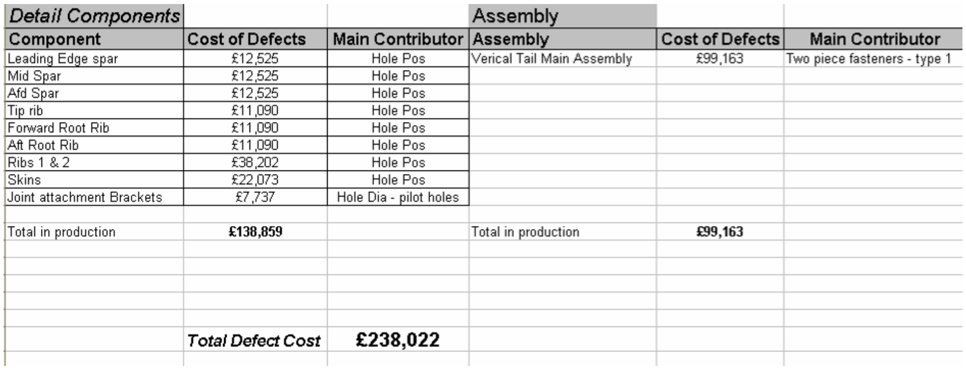
6.2.5.3 Trade Study 3

A further trade study is required to help reduce the defect costs arising in assembly. To help analyse where the main defect cost contributors are, the design evaluation tool highlights these areas to help direct trade studies. The author has added a further refinement to the tool, these are the sensitivity controls highlighted in figure 6.4. These reduce the sensitivity of the information shown by the tool and are used in three areas; main contributors, concessions and repair costs.

As a further detailed analysis of the assembly processes and key features is required, the sensitivity controller for the main contributor was increased to highlight more information. The design evaluation tool highlighted:

- Two piece, self torque fasteners are the largest contributor to defect costs in the assembly. The advantage of a self torque fastener system is that they are quick to install. With this advantage to the assembly it would be unwise to eliminate these without further investigation.
- Component installation, itself, is a major contributor to the defect cost. There may well be structural reasons for this particular type of component installation e.g. specific stress load on joints. To remove this type of installation would need further investigation by the structural engineering team.
- Two piece, manual torque fasteners, are also a major contribution to defect costs. These fasteners may be reduced if a blind fastener system, a one piece fastener system, can be used to install the final skin.
- Anchor nuts, would also be eliminated if blind fasteners are used.

The conclusions drawn from the above analysis is to introduce a further trade study to remove the two piece fastener system if possible, and replace it with a blind fastener system. This potential change to the design was input into the design evaluation tool so the changes to the defect costs can be highlighted. The summary sheet can be seen in figure 6.9. This trade study has introduced an additional reduction to achieve a total of over 41% from the initial proposed design



Detail Components			Assembly		
Component	**Cost of Defects**	**Main Contributor**	**Assembly**	**Cost of Defects**	**Main Contributor**
Leading Edge spar	£12,525	Hole Pos	Verical Tail Main Assembly	£99,163	Two piece fasteners - type 1
Mid Spar	£12,525	Hole Pos			
Afd Spar	£12,525	Hole Pos			
Tip rib	£11,090	Hole Pos			
Forward Root Rib	£11,090	Hole Pos			
Aft Root Rib	£11,090	Hole Pos			
Ribs 1 & 2	£38,202	Hole Pos			
Skins	£22,073	Hole Pos			
Joint attachment Brackets	£7,737	Hole Dia - pilot holes			
Total in production	**£138,859**		Total in production	**£99,163**	
	Total Defect Cost	**£238,022**			

Figure 6.9 – Results of the Re-design Trade Study 3 – Experimental phase 1

6.2.5.4 Critical Review from Senior Industrialists.

This experimental phase was presented to a number of senior industrialists engaged in the design and manufacture of aircraft, in particular a leading specialist in manufacturing engineering for airframe.

An in-depth demonstration and presentation was delivered by the author for a critical assessment of the design evaluation tool along with an assessment of the results from this theoretical experimental phase. A number of positive conclusions were drawn from the senior industrialists, in particular how powerful the tool was in allowing manufacturing engineering to deliver factual information into the design life-cycle enabling design for manufacturing to be considered so early in the design of the product.

A further positive application was highlighted in reducing the issue of designers using *“cut and paste engineering”*. This issue was highlighted by industrialists that a number of engineers merely design the product from previous designs and do not produce a design that addresses issues of current product design. The design engineer could be monitored on how effective their design is in addressing design for manufacturing issues.

From this assessment a number of questions were proposed to the author.

1. Could the design evaluation tool aid manufacturing in the areas of continuous improvement?
2. What are the major contributors to defect costs?
3. What process capability do manufacturing have to achieve?
4. Could a comparison of design be undertaken for a proposed alternative design and an existing design?

6.2.5.5 Answers to the questions proposed by Senior Industrialists.

The author answered the questions presented above in the following section.

1. Could the design evaluation tool aid manufacturing in the areas of continues improvement?

The design evaluation tool has been structured to identify the key features or processes that have a major contribution to the overall cost of defects. As discussed in the previous section the sensitivity control of the information can be simply adjusted to aid the engineer reviewing the data. The design evaluation tool offers an additional feature for this purpose; it not only identifies the major contributor but advises the engineer as to what would be the most beneficial action to take to optimise the proposed design. This is illustrated in figure 6.4. The design evaluation tool enables this to happen by advising the engineer to increase the upper specification limit or increase the lower specific limit.

2. What are the major contributors to defect costs?

The design evaluation tool has highlighted two key features that are contributing to the majority of the defect costs.

For the substructure components the hole positional tolerance is the major contributor. This single key feature contributes to over 25% of the defect costs. This was discussed in trade study 3 and the fact that the design tolerance cannot be increased. Taking this into consideration the design tolerance should remain with the manufacturing company introducing improvement initiatives to increase their manufacturing process capability for drilling holes. The author would advise investigation into the following areas: inspection methodology, improved cutting tools, machine set-up, and machine calibration etc.

The second area is the installation of the two piece fastener system, self torque. Trade study 2 has highlighted that this is a potential improvement area. However, the manufacturing assembly organisation could introduce an improvement initiative in this area to increase the process capability.

3. What process capability do manufacturing have to achieve?

To help with this question the author has used the key feature of hole position. Although the design evolution tool will not currently calculate the effect on the defect cost to different levels of process capability, by changing the process capability data, Cpk values, at regular intervals the effect on the cost can be relayed in a graphical format, see figure 6.10. This highlights that with the gradual increase in process capability comes a reduction in defect costs. The curve smoothes out at a Cpk of 1, the reason for this is that at this point the design evaluation tool introduces another major contributor.

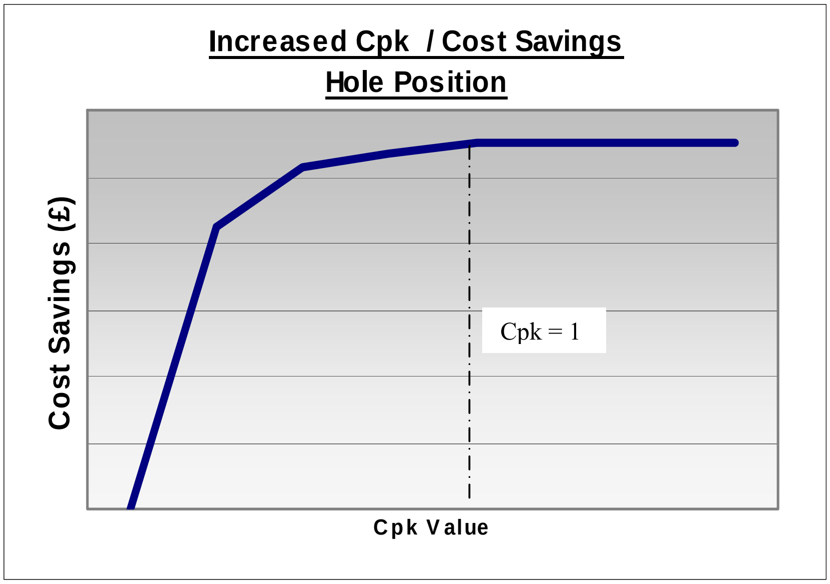


Figure 6.10 – Increasing Cpk and Related Cost Savings for Hole Position

For this experimental phase the design evaluation tool highlights that the reaming of hole diameter is contributing to the majority of the defect cost if the process capability is increased to a Cpk of 1. This may seem to be unacceptable to some manufacturing engineers and especially to Six Sigma specialists. However, what the design evaluation tool is doing is making the most optimum decision for the product as a whole; not just the feature. The author asks why increase the CPK to Six Sigma level when there are more cost effective savings to be made within the product? This increase in Cpk introduces a further cost saving to the original proposed design to reduce it by over 55%.

If the same analysis is introduced for hole diameter and the design evaluation tool is used to produce targets for the increase of process capability the defect costs are reduced further, figure 6.11 illustrates the results of this.

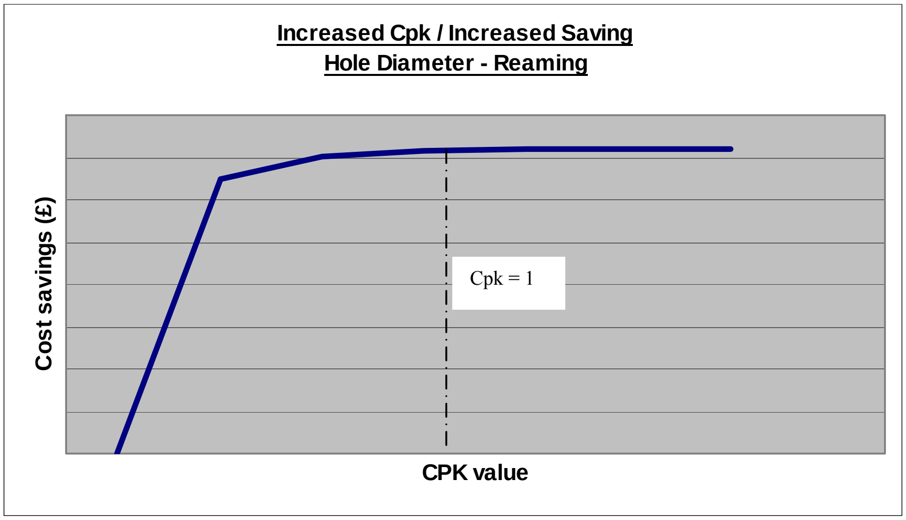


Figure 6.11 – Increase Cpk and its Related Cost Savings for Hole Diameter.

This increase in Cpk has reduced the cost by over 72% from the original design and a new major contributor to the defect cost is shown to be hole perpendicularity.

4. Could a comparison of a design be undertaken for a proposed alternative design and existing design?

The answer to the question posed to the author by lead industrialists is dependent on the level of detail that is present in design. With this taken into consideration the industrialists proposed a further experimental phase to the author. A large piece of aircraft structure was being reviewed for a redesign to aid manufacturing. It was recognised by the senior industrialist that prior to this research there was no way of measuring these potential additional costs at such an early stage in the design life-cycle. The results of the evaluation of the design are discussed in experimental phase 2.

6.2.6 Conclusion

The author has presented a representative theoretical design of a major piece of aircraft structure to enable the validation of the proposed design evaluation tool. Detail information was extracted from the design and input into the design evaluation tool to analyse how manufacturable the proposed design is. The defect costs, calculated by the tool, would be clearly unacceptable for a company to maintain.

The design evaluation tool structures the design information to enable three trade studies to be introduced to refine the design to aid design for manufacture.

Trade study 1 introduced a minor design change by increasing the tolerance of pilot hole diameter in substructure components. With the design change inputted into the tool it calculated a reduction in 7% in the costs associated to defects.

Trade study 2 introduced a more substantial design change by the omission of separate joint attachment brackets, replacing them with integral features on certain parts. This design change enabled a reduction on parts count on the assembly while maintaining structural integrity of the assembly. With these design changes adopted the total cost reduction from the initial proposed design rose to 33%.

Trade study 3 started to concentrate on the design features in the assembly. The tool highlighted that fastener installation was one of the main contributors to defect cost. With this information available, the fastener system in some areas was replaced with a blind fastener system. The outputs from this design change reduced the cost of defects by over 41% from the initial design proposed.

These outcomes generated by the design evaluation tool were presented for a critical review by senior industrialists in the aircraft industry. The author was met with a positive review of his work. A number of questions were posed to the author of which all have been addressed in the previous section. These introduced further analysis for the design evaluation tool. These produced targets of process capability indices that manufacturing companies need to achieve to reduce the overall cost of defects for the product; these have been named as manufacturing 1 and manufacturing 2. If these targets were to be achieved, it would increase the cost reduction from the design evaluation tool up to over 72% from the initial design.

A graphical summary of the reduced costs is illustrated in figure 6.12.

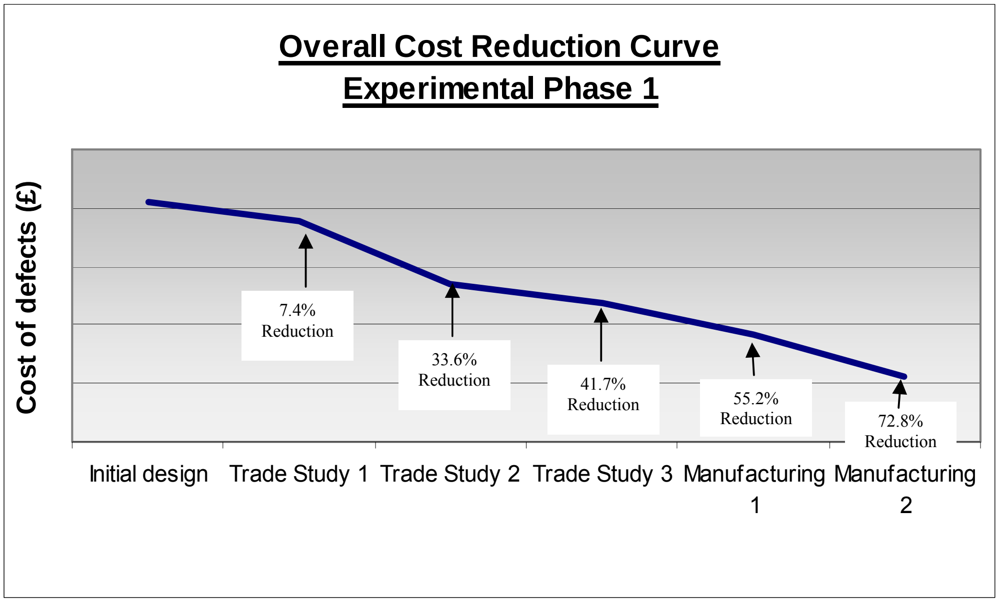


Figure 6.12 – A Summary of Cost Reduction from Experimental phase 1.

6.3 Experimental Phase 2

Design Evaluation of an Aircraft Structure Currently in Production.

6.3.1 Introduction

The results from experimental phase 1 were presented to senior industrialists within the aircraft industry. One of the outcomes of this was to analyse a design that is at an early stage in the design life-cycle and at conceptual or embodiment design phases discussed in chapter 5. The author was presented with preliminary design drawings to input into the design evaluation tool.

The aim of the experimental phase was to produce information around design for manufacture of the proposed design. The product selected for re-design is currently used on aircraft today. There had been a proposal to re-design that product to enable a cheaper method of manufacture, but currently there are no tools available to establish the manufacturability of a design, in the manner discussed previously by the author. This information is presented as a feasibility study as to whether the organisation should invest into a new design program me for the product.

6.3.2 Evaluation of Design Data

As detailed design information is limited for this product, the author had to conduct a number of interviews with specialists in the design and manufacturing engineering disciplines to collect necessary data. The specialists interviewed included the following:

- Design Engineers
- Structure Engineers

- Manufacturing Engineers – Substructure manufacturing
- Manufacturing Engineers – Assembly
- Manufacturing Engineers – Tooling
- Quality - Production

With the initial design information presented to the author and information gathered from these interviews, the proposed design intention could be derived.

With the design intent understood the author can start the process, discussed previously, of inputting the design data into the design evaluation tool. This consisted of the following:

Substructure Components

KC’s for typical spar type component (4 in total)

Datum A., Flatness

Datum B, hole diameter (ream), hole perpendicularity

Datum C, hole diameter (ream), hole perpendicularity, hole position

2 Location holes, hole diameter (drill), hole perpendicularity, hole position

3 Interface surface areas, surface profile tolerance

2 External surface areas, surface profile area

KC’s for typical spar type component (shorter in length 4 in total)

Datum A., Flatness

Datum B, hole diameter (ream), hole perpendicularity

Datum C, hole diameter (ream), hole perpendicularity, hole position

1 Location hole, hole diameter (drill), hole perpendicularity, hole position

2 Interface surface areas, surface profile tolerance

2 External surface areas, surface profile area

KC's for a typical stringer type component (2 in total)

Datum A., Flatness

Datum B, hole diameter (ream), hole perpendicularity

Datum C, hole diameter (ream), hole perpendicularity, hole position

1 Location hole, hole diameter (drill), hole perpendicularity, hole position

5 Interface surface areas, surface profile tolerance

2 External surface areas, surface profile area

KC's for a typical rib type component (16 in total)

Datum A., Flatness

Datum B, hole diameter (ream), hole perpendicularity

Datum C, hole diameter (ream), hole perpendicularity, hole position

2 Interface surface areas, surface profile tolerance

2 External surface areas, surface profile area

KC's for a bracket type component (14 in total)

Datum A., Flatness

Pilot holes, hole position

KC's for Skins (2 in total)

Datum A., Flatness

Datum B, hole diameter (ream), hole perpendicularity

Datum C, hole diameter (ream), hole perpendicularity, hole position

2 Location holes, hole diameter (drill), hole perpendicularity, hole position

2 Interface surface areas, surface profile tolerance

2 External surface areas, surface profile area

Assembly processes

Jig location of components (29 in total)

Part to part location of components (14 in total)

Shimming the joints, mouldable shim; for internal joints (20 in total)

Shimming joints, solid shim; for high loaded joints (10 in total)

Joint drilling manual (60 holes in total)

Auto drilling of skin and substructure (400 holes in total)

Anchor nuts installation (200 in total)

Fastener installation of joints, self torque (60 in total)

Fastener install of skin to substructure, self torque (200 in total)

Fastener install into nut plates, manual torque (200 in Total)

The author was presented with a further issue in this experimental phase, that there was limited process capability data and this is essential for the analysis of the design. One of the questions posed to the author in experimental phase 1, was whether the process capability data could drive the design to achieve a manufacturable product with low defect costs.

The design evaluation tool worked on a *"top down"* approach to evaluating the design. This would be the preferred way to evaluate the design, where the process capability data is used to measure how manufacturable the design is. However, the author found through a critical evaluation from industrial specialists that there may be scenarios where a *"bottom up"* approach is needed. This is where the process capability data is set for the manufacturing organisations to achieve. This type of information could be used in improvement studies. With this taken into consideration the author introduced an additional calculation, shown below, to enable the design evaluation tool to accommodate this feature. In summary it will enable the manufacturing engineer to input process capability data, in the form of Cpk, and the associated defect cost would be calculated in relation to the proposed design.

Chapter 5 explains how to calculate the CPK, once the standard deviation of the data is derived, using the following formula:

$$CPK = \frac{Z\min}{3}$$

The author has transposed the formula to calculate the standard deviation from a CPK value, *"bottom up"*. Two standard deviations are calculated for Z upper and Z lower the smallest value, Z min, is used for further calculations in the design evaluation tool. The formula for this is shown below:

Where

CPK = Process capability indices

Mean ($\bar{x}$) = the true mean

Standard Deviation (σ)

USL = Upper Specification Limit

LSL = Lower Specification Limit

$$\sigma\, Zupper = \frac{USL - \bar{x}}{CPK}$$

$$\sigma\, Zlower = \frac{\bar{x} - LSL}{CPK}$$

$$\sigma = \frac{\sigma\, ZMIN}{3}$$

Using this information the author will recalculate the experimental phase results in terms of cost in relation to the various Cpk values. Where only attribute data is available e.g. fastener installation, the author conducted a number of interviews with inspectors within production to verify the process capability data. From these results the attribute data was derived and linked to the relevant Cpk value. The proposed design will be evaluated with all the key features and processes set at the following process capability levels:

Process Capability Level	Cpk Values Variable data	% inspection points passed Attribute data
Level 1	Cpk of 0.4	82%
Level 2	Cpk of 0.5	85%
Level 3	Cpk of 0.75	88%
Level 4	Cpk of 1	92%
Level 5	Cpk of 1.2	95%
Level 6	Cpk of 1.33	98%

6.3.3 Results

The results of the design evaluation are illustrated in figure 6.13.

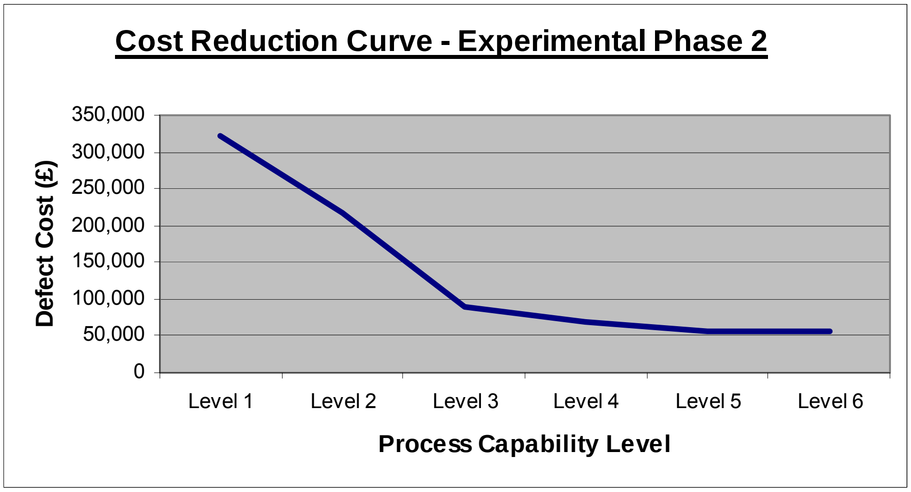


Figure 6.13 – A Summary of Cost Reduction from Experimental Phase 2.

The results are based on a production size of 10 and the results from the evaluation were what would be expected given the reduction in process capability; hence a reduction in defect costs. What the results give, in such an early stage of the design life-cycle, is a clear view of the effect the design will have not just on manufacturing but on the company profits as a whole. The design team have a clear tangible starting point for the design for manufacturability of their product and as more accurate process capability data is input into the design evaluation tool the more closely the data will reflect the design.

6.3.4 Conclusion

Preliminary design information was presented to the author during a critical review of experimental phase 1 results. The aim of this experimental phase was to evaluate a potential design that is early in the design life-cycle, conceptual or embodiment phase. This will enable the engineering leads to review tangible information, such as cost, to establish the effect on the product and the business, if the proposed design went through to manufacture.

As the author was presented with little detailed design information, a series of interviews were undertaken to establish the intention of the design. These interviews involved a range of engineering disciplines in the design and manufacturing teams. Once the author had a clearer view of the design intent the collective outputs were input into the design evaluation tool in the form of key features and process.

Within the aircraft industry, process capability information can be considered as the *"crown jewels"* of their manufacturing process. It can be a measure of company's strengths and weaknesses in its manufacturing processes. When developing a new design, different methods of manufacturing may be developed in parallel to deliver the customer requirements. In this case process capability data may not exist. With this in mind the author introduced a range of process capability levels to which the design key features and processes can be accessed.

The main advantage of the model at this stage in the design life-cycle is to establish a base line to which the design team can mature the design into a manufacturable design while ensuring the customer's requirements are maintained. As the design develops through the design life-cycle any changes can be quickly evaluated.

The main purpose of the experimental phase is to aid in the decision making on whether to continue with a new design to enable a different manufacturing route than is currently being used by the company. The results of this experimental phase were presented to the industrialists to aid their decision on whether to progress with the new design proposal. With the above design for manufacture data the industrialists reached a conclusion not to continue with the proposed re-design.

6.4 Experimental Phase 3

A Comparison between the Design Evaluation Tool and the Actual Results from Manufacturing an Aircraft Structure in Production.

6.4.1 Introduction

To demonstrate the above methodology a third experimental phase was undertaken in the research process, looking at the evaluation of a major section of aircraft structure that was currently being manufactured. The aim of this experimental phase was to evaluate the design and analyse the results, then to compare them with the actual defects that were found. The design evaluation tool produces an estimation of defects that may arise when the design goes into manufacture and from this data a concession count can be estimated. Unlike other manufactured products, if a defect occurs (when the component has been manufactured outside the design specification) a waver or concession has to be issued to verify that the defect is acceptable to use on the product. For this assessment to be complete it needs to be reviewed by a number of engineering disciplines within the organisation. On completion of this detailed analysis the product will or will not be authorised for flight. There is no “grey” area for this.

This process, which is in place to ensure aircraft safety, is costly to the industry and the aim of this experimental phase is to validate the accuracy of the design evaluation tool to predict the type of defects and number of concessions that are produced

The design information will be loaded into the design evaluation tool along with the process capability data; this will enable the tool to estimate the level of defects. The tool outputs will be measured against the actual defects recorded by manufacturing. The author will conclude the experimental phase by identifying the major areas that contribute to defect costs of the product.

The author has made a number of aesthetic refinements to the tool from those presented in experimental phase 1 and 2.

6.4.2 Evaluation of Design Data

The current design was reviewed in detail by the author and all the key characteristics were extracted as discussed in chapter 5. A summary of the data that was input into the design evaluation tool is listed below:

Product Features

Total number of substructure components	29
Total number of KC's analysed by the design evaluation tool	210
Total number of opportunities for defect within the KC's	5,049

Cost data

Five hourly cost rates have been used to calculate the defect costs, their values were verified by the organisation:

Hourly charging rate for repairing a substructure component on a machine.

Hourly charging rate for repairing a substructure component off a machine.

Hourly charging rate for repairing the assembly on a machine.

Hourly charging rate for repairing the assembly off a machine.

Estimated cost for issuing a concession.

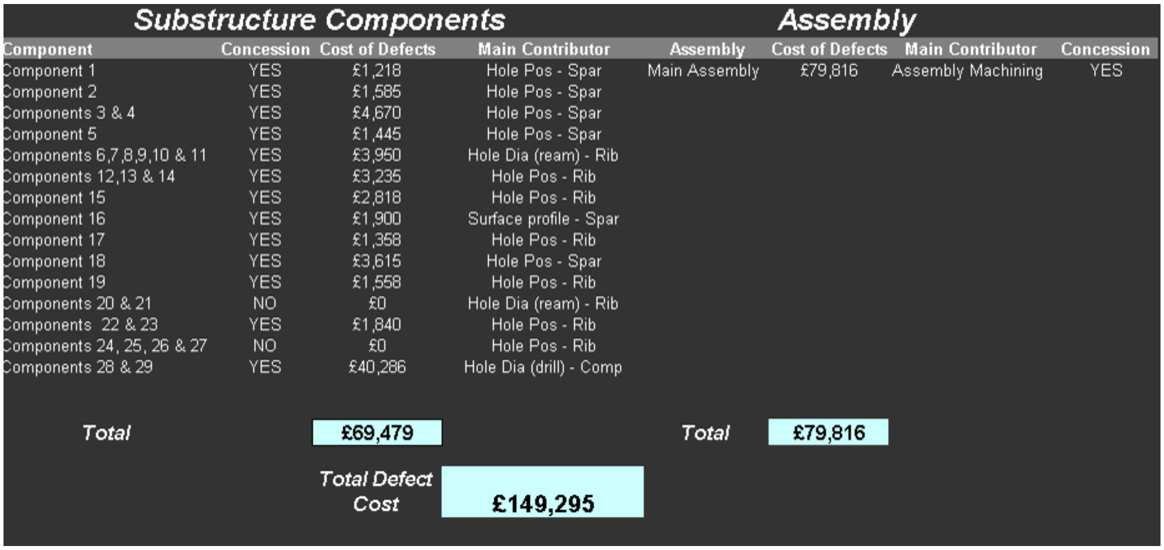
The estimated repair time for each key characteristic that is either below or above the design specification has been loaded into the design evaluation tool. Details of which can be seen in appendix 2

Process Capability data

The third section of data which is required is the process capability data. The author loaded in excess of 10,000 points of process capability data to analysis the design. This inspection data for each of the key characteristics has been loaded into the tool. Two types of inspection data have been used; variable data, this is where exact location points have been taken on the location of a feature, usually by a CMM. Attribute data is where there is a only a two-way or binary classification given, for example a component fitment would be classified as yes or no. In the assembly section of the design evaluation, some of the attribute process capability data was not available. It is crucial that there is process capability data present for each key process to ensure an accurate evaluation of the design. To ensure this the author undertook a number of expert interviews with inspectors and senior quality controllers who actually inspected the products and the outcomes of the key processes in assembly. The interviews resulted in a consistent view of the process capability. With this information now available accurate data was input into the design evaluation tool.

6.4.3 Comparison of Results

The summary sheet from the design evaluation tool is shown in figure 6.14



Substructure Components				Assembly			
Component	Concession	Cost of Defects	Main Contributor	Assembly	Cost of Defects	Main Contributor	Concession
Component 1	YES	£1,218	Hole Pos - Spar	Main Assembly	£79,816	Assembly Machining	YES
Component 2	YES	£1,585	Hole Pos - Spar				
Components 3 & 4	YES	£4,670	Hole Pos - Spar				
Component 5	YES	£1,445	Hole Pos - Spar				
Components 6,7,8,9,10 & 11	YES	£3,950	Hole Dia (ream) - Rib				
Components 12,13 & 14	YES	£3,235	Hole Pos - Rib				
Component 15	YES	£2,818	Hole Pos - Rib				
Component 16	YES	£1,900	Surface profile - Spar				
Component 17	YES	£1,358	Hole Pos - Rib				
Component 18	YES	£3,615	Hole Pos - Spar				
Component 19	YES	£1,558	Hole Pos - Rib				
Components 20 & 21	NO	£0	Hole Dia (ream) - Rib				
Components 22 & 23	YES	£1,840	Hole Pos - Rib				
Components 24, 25, 26 & 27	NO	£0	Hole Pos - Rib				
Components 28 & 29	YES	£40,286	Hole Dia (drill) - Comp				
Total		£69,479		*Total*	£79,816		
		Total Defect Cost	£149,295				

Figure 6.14 – Summary Results from the Design Evaluation Tool – Phase 3

The summary sheet from the design evaluation tool highlights the main contributors to cost. If more detailed information is required about which area of the product contributes to the overall cost, the user can interrogate the individual sections of the design evaluation tool. The author has analysed the results in more detail, these are shown below:

Substructure Parts Evaluation

Out of the total defect cost associated to the design almost 38% is contributed by the cost of reworking the components back to design specifications, with over 7% of the cost being allocated to issuing concessions.

The main key characteristics that contribute to these costs are;

- Hole position, the design evolution tool has highlighted that this is the major contribution to cost for 14 components.

- Hole diameter, the design evolution tool has highlighted that this is the major contribution to cost for 13 components.
- Surface Profile, the design evolution tool has highlighted that this is the major contribution to cost for 2 components.

Due to these defects in manufacturing, to enable the substructure components to be used on the aircraft, 89% of them will require a concession to be issued from the engineering team.

Assembly Evaluation

Out of the total defect cost associated to the design over 82% is contributed by the cost of reworking the components, due to defects in manufacturing, back to the design specifications, with over 7% of the cost being allocated to issuing concessions. The main key characteristics that contribute to these costs are;

- Assembly machining, the design evolution tool has highlighted that this contributes to almost 87% of the overall rework cost associated to the assemble processes.
- Two piece fasteners – self torque, the design evolution tool has highlighted that this contributes to almost 6% of the overall rework cost associated to the assemble processes.
- Two piece fasteners – manual torque, the design evolution tool has highlighted that this contributes to almost 2% of the overall rework cost associated to the assemble processes.
- Anchor nuts – bonded, the design evolution tool has highlighted that this contributes to over 1% of the overall rework cost associated to the assemble processes.

These results a detailed in figure 6.15

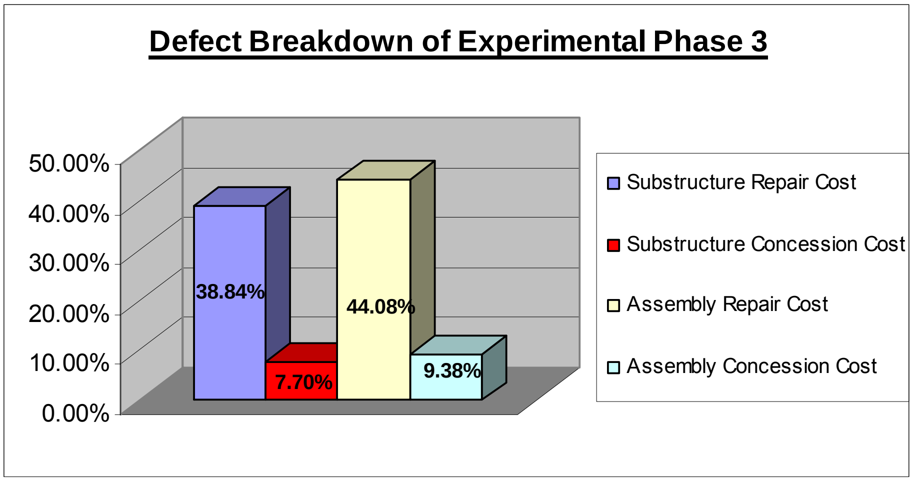


Figure 6.15 – Result of Defect Areas – Experimental Phase 3

To enable the components to be used on the aircraft, after the assembly processes have been applied, 77% of them will require a concession to be issued from the engineering team.

With this more detailed review of the design evaluation tool the results clearly show that the majority of the costs, over 53%, are associated with the assembly processes.

To validate this data, the author has undertaken further analysis as to what the actual inspection data showed in relation to the manufactured design. The author extensively reviewed all the non-conformance data that was produced from the manufacturing of the substructure parts and the assembly of the entire product.

On review of the information the author omitted a considerable number of submitted concessions due to the irrelevance to the features evaluated. This included requests for alternatives, e.g. material, fasteners etc. If a standard part, e.g. fastener, or material is not available it will stop manufacturing of substructure or the assembly. Due to traceability of all products used on the aircraft, alternative products need to be authorised by the engineering team and the identification of its use needs to be highlighted on the specific aircraft's records. As the assembly will not be to the design specification, a concession or waiver is required to authorise the use of the alternative product.

The author has undertaken a comparison of the data from the design evaluation tool and the submitted concessions. During the comparison of results, in some areas, the author had to conduct a more detailed investigation of the inspection results. This involved investigation into the methods of inspection, the detail of this is discussed below.

The design evaluation tool has been developed to include sensitivity markers for each product, discussed previously and illustrated in figure 6.4 Concession sensitivity control can be used to balance the specific part or assembly. These have been developed to help control the data in the *"grey area"*. The author refers to this in this manner as there is no *"black"* or *"white"* in this area. There is always a proportion of data that falls within this *"grey"* area. What the sensitivity control does is to move these areas around its nominal. The current setting is at *"average"* if the design evaluation tool is predicting more concession than are submitted. The *"grey area"* can be reduced by selecting control "-" to further reduce this "- -" can be selected. The opposite applies with controls "+" & "++". The author will adjust these during the comparison.

The number allocated to each key characteristic is the scale to which the design evaluation tool predicts the likelihood of it generating a concession, 1 being the highest. The markers at the end of each feature indicate the position the sensitivity marker is set to. If there is no marker at the end of the feature this indicates that when the sensitivity has been set as average the design evaluation tool has not highlighted this as having potential to generate a concession.

Component 1

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	-	- -	Hole Position
2. Surface Profile	-	- -	Surface Profile
3. Hole Diameter	-		
4. Hole Perpendicularity			

For this component the design evaluation tool has predicted correctly the key features that would generate a concession in manufacturing.

The sensitivity marker has been set to “- -“, this will ensure a more accurate prediction of concessions for further concessions.

Component 2

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	-	- -	Hole Position
2. Surface Profile	-	- -	Edge of Part
3. Hole Diameter	-	- -	

For this component the design evaluation tool has correctly predicted that hole position would be a potential contributor in the generation of a concession in manufacturing. An edge of part defect occurred that the design evaluation tool did not predict, therefore the author investigated the inspection methodology and CMM inspection data, this is illustrated in figure 6.16.

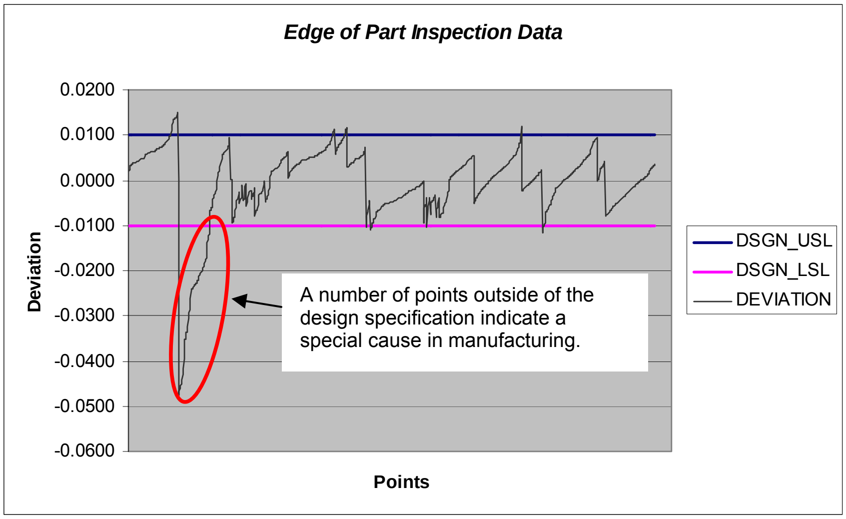
The inspection data verified that *"something"* occurred in the manufacturing process that does not fit in with the majority of the process capability data. This is referred to as a special cause, where an issue such as operator error occurred during manufacturing.

The sensitivity has been left as per the original evaluation, *"average"*

Component 3 & 4

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	**-**	**- -**	Surface Profile
2. Surface Profile	-	- -	Edge of Part
3. Hole Diameter	-	- -	

For these components the design evaluation tool has predicted correctly that surface profile would be a potential contributor in the generation of a concession in manufacturing, however the predicted main contributor is not present. The method of manufacture and inspection is similar to component 2. The fact that this issue occurs on similar products where both manufacturing and inspection methodologies are the same, enforces the author's conclusion. An edge of part error has been submitted in a concession and the design evaluation tool gave no indication that it would be a potential issue. The author investigated the error in question by studying the CMM inspection data, this is illustrated in figure 6.16



A number of points outside of the design specification indicate a special cause in manufacturing.

Figure 6.16 – Results from Edge of Part Inspection Data – Experimental phase 3

The inspection data verified that *"something"* occurred in the manufacturing process that does not fit in with the majority of the process capability data. This is referred to as a special cause, where an issue such as operator error occurred during manufacturing.

The sensitivity has been left as per the original evaluation, *"average"*

Component 5

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	-	- -	Surface Profile
2. Surface Profile	-	- -	
3. Hole Diameter			
4. Hole Perpendicularity			

For this component the design evaluation tool has predicted correctly that surface profile would be a potential contributor in the generation of a concession in manufacturing. However the predicted main contributor is not present, the author investigated the inspection methodology. The component is inspected around the datum holes, therefore if a datum hole is out of position it would make the whole component out of position. With this taken into consideration it would have an impact on the surface profile in relation to the datum holes, hence an increase in surface profile error.

The sensitivity marker has been set to “-“, this will ensure a more accurate prediction of concessions for further products.

Components 6, 7, 8, 9, 10 & 11

Design Evaluation Tools Results		**Submitted Concessions**
1. Hole Position	-	Hole Position
2. Surface Profile		Surface Profile

For these components the design evaluation tools has predicted correctly the key features that would generate a concession in manufacturing.

Only two concessions were issued for these products with the design evaluation tool accurately prediction their outcome. When the sensitivity controller is adjusted to “-“ only one feature remains, when adjusted to “- -“ no features are highlighted. This supports why not all of the components had concession issues against them, with only a medium chance of a concession arising.

The sensitivity has been left as per the original evaluation, *“average”*

Components 12, 13 and 14

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	-	- -	Hole Position

2. Hole Diameter	-		
3. Surface Profile			

For these components the design evaluation tool has correctly predicted the key feature that would generate a concession in manufacturing.

The sensitivity marker has been set to “- -“, this will ensure a more accurate prediction of concessions for future products.

Components 15

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	-	- -	Hole Position
2. Surface Profile	-		Surface Profile
3. Hole Diameter	-		

For component 15 the design evaluation tool has correctly predicted the key features that would generate a concession in manufacturing.

The sensitivity marker has been set to “- “, this will ensure a more accurate prediction of the concessions in the future.

Components 16

Design Evaluation Tools Results			**Submitted Concessions**
1. Surface Profile	-	- -	Hole Position
2. Bore Diameter	-		
3. Hole Position	-		

4. Bore Position

For component 16 the design evaluation tool has correctly predicted the key features that would generate a concession in manufacturing. It has been noted however that there are no errors on the bore, which was the second highest contributor from the design evaluation tool. Although no errors have been submitted, after reviewing the data the author still believes that this is a contributor to defects.

The sensitivity marker has been set to “- “, this will ensure a more accurate prediction of the concessions in the future.

Components 17

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	**-**	**- -**	Surface Profile
2. Hole Diameter	-		Hole Positional
3. Surface Profile	-		

For this component the design evaluation tool has correctly predicted that hole position and surface profile would be a potential contributor in the generation of a concession in manufacturing.

The sensitivity has been left as per the original evaluation, *“average”*

Components 18

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Position	**-**	**- -**	Bore Position
2. Surface Profile	-	- -	

3. Hole Diameter -

4. Bore Diameter -

5. Bore Position

6. Width

The key characteristics that have been submitted via a concession were highlighted as main contributors by the design evaluation tool, with the bore position highlighted

A bore positional error has been submitted in a concession, the design evaluation tool gave a low indication that it would be a potential issue. The author investigated the error in question by analysing the CMM inspection data; this is illustrated in figure 6.17.

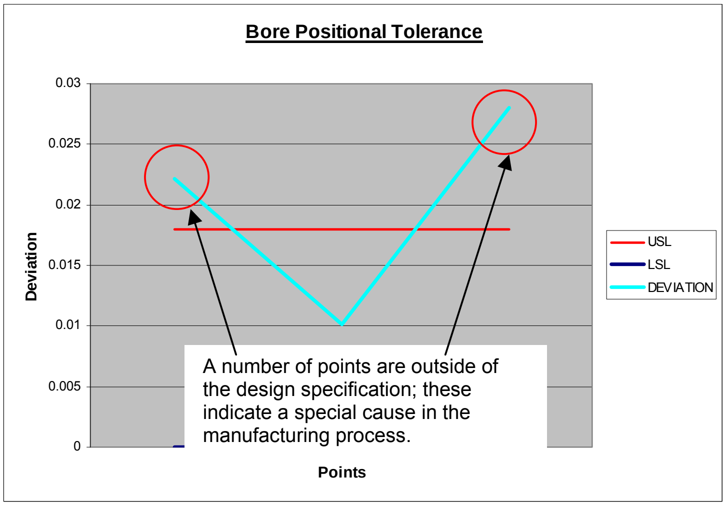


Figure 6.17 – Results from Bore Position Inspection Data – Experimental Phase 3

The first concern the author highlights is the lack of points in the process capability data as this will not represent a true indication of process capability data. As more parts with the key features are recorded, the more reliable the data will be. The review of the inspection data verified that something occurred in the manufacturing process that does not fit in within the design specification. This is referred to as a special cause, where an issue such as operator error occurred during manufacturing.

The sensitivity has been left as per the original evaluation, *“average”*

Components 19

Design Evaluation Tools Results			**Submitted Concessions**
1. Hole Diameter	**-**	**- -**	Surface Profile
2. Hole Position	-	- -	Hole Position
3. Surface Profile	-	- -	Hole Perpendicularity

For this component the design evaluation tool has predicted correctly the key feature that would generate a concession in manufacturing, surface profile and hole position. An additional feature, hole perpendicularity, that was not predicted by the design evaluation tool has been submitted as a concession, as in previous cases the author recommends to treat this as a special cause.

The sensitivity has been left as per the original evaluation, *“average”*

Components 20 and 21

Design Evaluation Tools Results	**Submitted Concessions**
No defects where predicted	Bore Position
	Surface Profile
	Hole Perpendicularity

The design evaluation tool calculated that there would be no concessions with the sensitivity controller set at *"average"*. If the sensitivity control increased the width of the calculation, "+" or "++", it would indicate the potential of key features generating a concession. This is what was seen from the information presented from the manufacturing company that these key features where present in an issued concession.

The sensitivity has been left as per the original evaluation, *"average"*.

Components 22 and 23

Design Evaluation Tools Results	**Submitted Concessions**
No defects where predicted	No concessions where submitted

For these components the design evaluation tool has predicted correctly that no key features would generate a concession in manufacturing.

The sensitivity has been left as per the original evaluation, *"average"*.

Components 24, 25, 26 and 27

Design Evaluation Tools Results	**Submitted Concessions**
No defects where predicted	No concessions where submitted

For these components the design evaluation tool has predicted correctly that no key features would generate a concession in manufacturing.

The sensitivity has been left as per the original evaluation, *"average"*.

Components 28 and 29

Design Evaluation Tools Results	**Submitted Concessions**
1. Hole Diameter	Hole Diameter
2. Flatness	Edge of Part
3. Skin Thickness	Countersink Error

For this component the design evaluation tool has predicted correctly the key feature that would generate a concession in manufacturing, hole diameter. The additional feature, edge of part, was identified from the concession data. If the sensitivity was increased in the design evaluation tool it would of correctly predicted this as contributor. A further contributor was present in the concession data, Countersink depths of holes. This was not identified as a feature in the design evaluation tool; the author recommends an investigation into these designed features.

The sensitivity has been left as per the original evaluation, *"average"*

Assembly Evaluation

Numbers in brackets denotes the estimated number of Concessions

Design Evaluation Tool Results	**Submitted Concessions**
1. Assembly Machining (2)	Hole Diameter - Structure
2. Two Piece Fastener – Self Torque (2)	Hole Diameter - Structure
3. Two Piece Fastener – Manual torque (3)	Hole Diameter - Structure
4. Anchor Nut – Bonded (1)	Hole Diameter - Auto
5. Hole Diameter – Auto (2)	Two Piece Fastener – S Torque
6. Anchor Nut Riveted (1)	Anchor Nut Riveted

7. Structural Gap Condition (1)	Anchor Nut Bonded
8. Shimming Joints (1)	Hole Diameter - Structure
9. Rivet Installation (1)	Assembly Machining

The first area that this comparison has highlighted is the number of concessions that have been issued for structural drilling where the design evaluation tool has not highlighted this as a contributor to defects. A future investigation by the author highlighted that given a practical view of structural drilling process it had a high chance of creating a defect. This was due to the amount of *"free hand"* drilling that takes place; this was supported by the fact that 45% of all concessions submitted during assembly of the product were structural drilling defects.

With the above facts considered the author interrogated the inspection data of this process, the variability graph, figure 6.18, highlights these results.

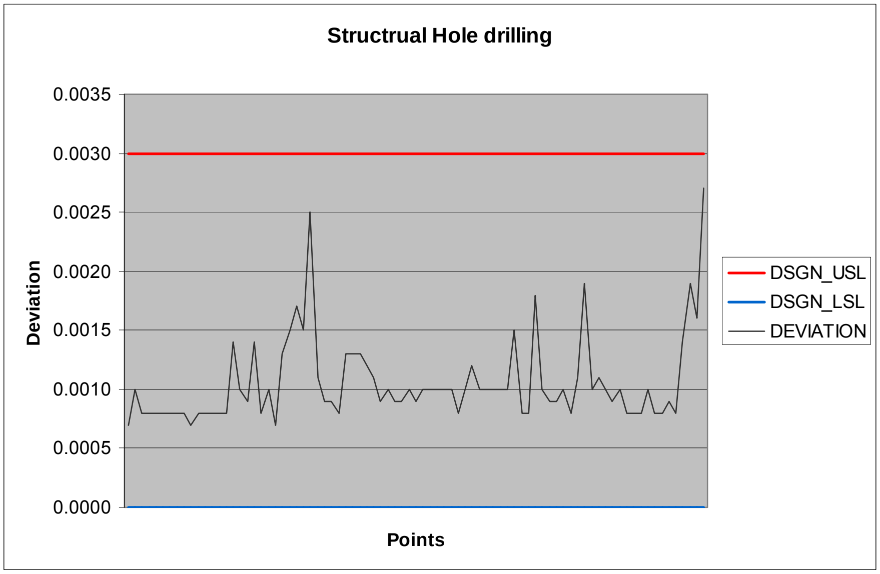


Figure 6.18 – Results from Structural Drilling in Assembly – Experimental phase 3

The results in figures 6.18 clearly highlight that the process is in control with no points outside the design tolerance. This indicated that the design evaluation tool was calculating the defects correctly. Interviews with the inspectors in the assembly manufacturing company highlighted there was a process failure in collating the process capability data. The inspectors were only submitting the inspection data to the process capability database if they where correct. Any holes that were outside tolerance were loaded to the non-conformance data base for corrective action to be issue, via a concession. The author highlighted this failure to the manufacturing areas for resolution.

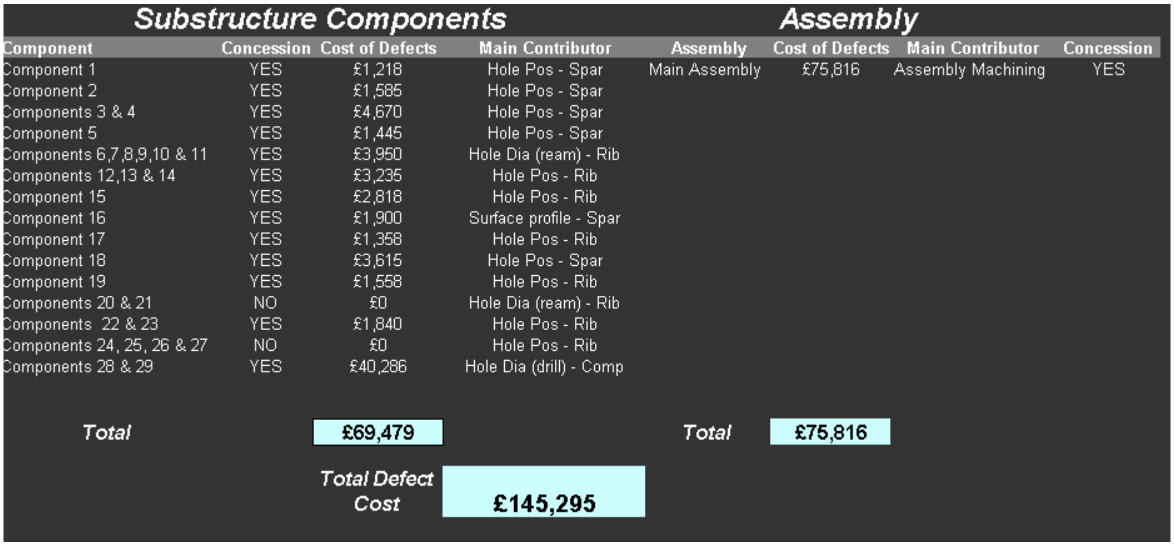
The design evaluation tool has correctly highlighted that the highest contributor to defects is assembly machining where concessions have been submitted for these defects. The tool also highlighted that hole position, two piece fasteners – self torque, anchor nut – riveted and anchor nut – bond would be the key processes that would generate a concession, concessions where submitted for all of these areas.

Analysing the predicted defects and the actual defects submitted, the author highlights that more defects were predicted than were actually submitted. After further investigation into these issues it was clear what the reason was for this. Most of the processes that were highlighted as being potential defects would not generate a concession, for example if a bonded anchor dis-bonded from the structure the operations personal would simply replace the defective part. No engineering action would be required for a defect of this nature as it is still maintaining the current design specification. Most of the defects in this area will be treated in this manner with the only exception being if the defect damaged the surrounding structure. Taking this issue into consideration the author has changed the sensitivity controller to “- -“. This adjustment to the tool has reduced the prediction of concessions to 10 with the top seven contributors remaining; this will enable a more accurate prediction from the design evaluation tool for future builds. This change is supported by the results from the number of concession that have been submitted from the manufacturing company.

After the structure drilling concessions have been removed, as discussed previously, 6 concessions are remaining with all the defects predicted by the design evaluation tool.

The author highlights that although concessions will not be submitted, the cost for reworking these back to design requirements is still present and should be continually analysed and predicted by the design evaluation tool.

The results to the overall cost of defects after the author has introduced the sensitivity controls are highlighted in figure 6.19. These changes to the sensitivity controls will help produce more accurate predictions of concessions for future builds.



Substructure Components				Assembly			
Component	Concession	Cost of Defects	Main Contributor	Assembly	Cost of Defects	Main Contributor	Concession
Component 1	YES	£1,218	Hole Pos - Spar	Main Assembly	£75,816	Assembly Machining	YES
Component 2	YES	£1,585	Hole Pos - Spar				
Components 3 & 4	YES	£4,670	Hole Pos - Spar				
Component 5	YES	£1,445	Hole Pos - Spar				
Components 6,7,8,9,10 & 11	YES	£3,950	Hole Dia (ream) - Rib				
Components 12,13 & 14	YES	£3,235	Hole Pos - Rib				
Component 15	YES	£2,818	Hole Pos - Rib				
Component 16	YES	£1,900	Surface profile - Spar				
Component 17	YES	£1,358	Hole Pos - Rib				
Component 18	YES	£3,615	Hole Pos - Spar				
Component 19	YES	£1,558	Hole Pos - Rib				
Components 20 & 21	NO	£0	Hole Dia (ream) - Rib				
Components 22 & 23	YES	£1,840	Hole Pos - Rib				
Components 24, 25, 26 & 27	NO	£0	Hole Pos - Rib				
Components 28 & 29	YES	£40,286	Hole Dia (drill) - Comp				
Total		£69,479		Total	£75,816		
		Total Defect Cost	£145,295				

Figure 6.19 – Results from the Summary Sheet after the Sensitivity Controls have been Applied – Experimental Phase 3

6.4.4 Conclusion

The author has introduced the reader to three experimental phases, used to validate and test the proposed design evaluation tool and the research methodology.

The first experimental phase, Validation of Process on a Theoretical Study of an Aircraft Tail, was to ensure that the various inputs to the design evaluation tool where correctly calculated to produce valid output data. The aim was to verify a valid base of calculations which subsequent experimental phases can use. Once the input data was introduced into the tool it produced valid cost results along with a clear direction to the potential cost reduction areas that could be introduced to the design. With direction from the design evaluation data, three separate cost reduction studies were introduced as *"trade studies"*. These introduced changes to areas in the design which reduced the potential of defects occurring in manufacturing, hence a more manufacturable design. These changes to the design where inputted and the tool calculated a reduction in defect costs in excess of 41%.

These results where presented to industry leaders in this field who proposed further developments to the tool. The most substantial being a *"bottom up"* approach to the design evaluation. This required the design evaluation tool to direct manufacturing in cost reduction activities by producing an optimum process capability level. This introduced further cost savings to the proposed theoretical design to a total saving of 70% from the original design.

The second experimental phase, Design Evaluation of an Aircraft Structure which is currently in Production, derived from a question posed to the author from a critical review from lead industrialists in experimental phase 1. This was to analyse a design that is early in the design life-cycle to aid a decision whether to introduce this new design on an existing product. The author produced a design evaluation model of the proposed design, validated in experimental phase 1, producing not only what the cost of defects the company would incur if the design was to be introduced, but further direction to the design team and the manufacturing organisation as to where improvements could be made. These results where presented to the lead industrialists.

The third experimental phase, Design Evaluation of an Aircraft Structure Currently in Production introduced the reader to a comparison between the design evaluation and an existing design that is in current manufacture. The calculated outputs from the design evaluation tool were compared with the submitted defects from manufacturing. This gave a true evaluation of the author's design evaluation tool. This experimental phase highlighted that a large amount of the outputs produced by the design evaluation tool corresponded to the actual defects submitted by the relevant manufacturing organisations. The few areas that did not correspond were investigated and results were discussed

These cases studies have verified the robustness of the author's design evaluation tool, with the results clearly indicating that it introduces a tangible measurement to the manufacturability of the design evaluated. With results indicating that for manufacture of substructure components the design evaluation tool predicted correctly 93% of defects that actually occurred, with 68% accuracy in identifying the main contributors to defects, the assembly analysis was as successful, producing higher accuracy in it predictions

It has been also verified that if the design is changed, using the outputs from the tool, to enable a more manufacturable design the improvements can be seen. This type of information can be used to monitor how effective an individual designer is in their adoption of design for manufacture. This chapter also introduced a *"bottom up"* approach to reducing costs, by issuing the manufacturing process improvement teams with targets to their process capability.

Chapter 7 Conclusion and Recommendations for Further work

7.1 Introduction

The area of design for manufacture has been subject to research over the past few years. The author believes that he has achieved the original research objectives, including contributing to existing knowledge. The research has also resulted in the identification of a number of areas that would benefit from further research. This chapter will summarise the findings of the research and will conclude with suggestions for future research.

7.2 Meeting Research Objectives

The research objectives were defined at the outset of the research project and discussed in Chapter 1. The author has highlighted each objective below discussing how he has achieved the objective through his research:

Objective 1: To review the literature to establish current general approaches to product design.

This objective was met by an extensive Literature Review, Chapter 2. This examines and discusses a range of past and current design life-cycle models, design environment models and so establishes approaches to design and manufacture tools reviewing their strengths and weaknesses.

Objective 2: To review current approaches in the design life-cycle and design for manufacture in the design of low volume, highly complex products. Review techniques that enable design for manufacture to be deployed into the design life-cycle.

This objective was achieved by the author discussing his findings from the literature review and concluded that whilst the area for design for manufacture has been extensively researched by academics such as Boothroyd and Dewhurst, the literature which discussed design for manufacture in the areas of low volume high complexity products is in short supply and none of the approaches effectively integrates design for manufacture into the design life-cycle.

Objective 3: To develop a novel improved design life-cycle model that caters for the design of low volume and high complexity products that emphasises adherence to customer requirements, controlling the design inputs to achieve the desired outputs.

The author observes that the literature covering the area of low volume high complexity products is sparse and that none of the approaches effectively integrates design for manufacture into the design life-cycle. The author discusses the problems posed by this in Chapter 4. He then outlines possible solutions and goes on to propose a novel design life-cycle model which includes design for manufacture for low volume high complexity products in Chapter 5. The chapter discusses the novel design life-cycle model which controls the design of a product with two features. Firstly the three key drivers: Requirement Definition, Review Gates and a Decision Maker. Secondly the seven phases of the design: Requirements Definition, Conceptual Design, Embodiment Design, Detail design, Production Planning, Manufacturing and Maintenance and Support.

Objective 4: To categorise the current design environments that the design life-cycle operates in, analysing their strengths and weaknesses and identifying which environment would benefit a low volume high complexity product during its design.

The author meets this objective by introducing the reader to four alternative design environments in chapter 5 and proposes a selection tool that will enable an organisation to understand the main advantages and disadvantages encountered from operating in this specific environment. The tool aids the selection of the most appropriate environment for an organisation to operate in. Industrial specialists, in the area of aircraft design and manufacture, populated the author’s section tool. The results highlighted that a concurrent environment best fit their requirements.

Objective 5: To produce a novel design for manufacture tool that can be used in the author's novel design life-cycle to access how decisions made during the design stage will affect the overall cost and quality of the product when in manufacture.

This objective was met by introducing the reader to his design evaluation tool where Chapter 4, Background to the Problem concluded that this was the main area of contribution to existing knowledge within the author’s research. The author in Chapter 5 introduces the reader to his novel design evaluation tool discussing its framework and how it should be used alongside the proposed design life-cycle. The inputs from the designs are mathematically analysed to produce tangible outputs, for example cost of rework, cost of concessions, number of concessions, number of detects etc. These can be quantified to establish the design manufacturability. The validation and test of the design evaluation tool is discussed in Chapter 6 where three experimental phases are used to validate the design evaluation tool: Validation of the Process on a Theoretical Study of an Aircraft Tail, Design Evaluation of an Aircraft Structure Currently in Production and A Comparison between the Design Evaluation Tool and the Actual Results from Manufacturing an Aircraft Structure in Production

The author highlights the fact that the design evaluation tool will undergo modifications and improvements as it develops and is implemented into product design. However, the research has contributed to existing knowledge by enabling the manufacturability of the design to be measured within the design life-cycle and introduces a revolutionary design evaluation tool into the digital environment of the design and manufacture of aircraft parts. This validated tool is the main contribution to existing knowledge delivered by the research.

7.3 Research Contributions to Knowledge

This research has looked into the area of design for manufacture during the design of low volume large complex products such as aircraft. There are three areas in which the author contributes to existing knowledge.

Firstly the environment in which the design life-cycle operates is an important consideration when designing a product. The author produced a novel selection tool to aid in this decision and this is discussed in Chapter 5.2. From a literature search and the results from expert interviews, the author found that there was little understanding of what would be the best environment for a design life-cycle to operate in for high complex low volume products, such as aircraft. This tool helps organisations to best structure the most appropriate environment, it was concluded that a concurrent environment would be the most effective when designing an aircraft.

Secondly, Chapter 5.3 introduces a novel design life-cycle that enables a structured approach in the design of high complex products such as aircraft. During a literature search and expert interviews the author concluded that a structured approach is essential when controlling large amounts of technical data. Current published knowledge did not answer all of the concerns from the author’s findings. To fill this gap in current knowledge the author introduced a new design life-cycle based on seven phases; requirements definition, conceptual design, embodiment design, detail design, production planning, manufacturing, and maintenance / support. These distinct steps help structure a complex developing design. To control the complexity of the data mass, three main drivers are introduced; requirements definition, review gates and a decision maker. After these phases and drivers had been developed it became apparent that is was difficult for manufacturing engineers to introduce tangible data at the review gates. By finding a solution to this problem the author made a significant contribution to knowledge in the area of design for manufacture.

The third and most extensive contribution to knowledge by the author was the introduction of a novel design evaluation tool. The research highlighted the need for manufacturing engineering to have the ability to assess the design for manufacturability. The author realised that a solution to this problem would produce a major contribution to knowledge in design for manufacturing. The key characteristics are selected from the design and using manufacturing process capability data, they are then mathematically analysed to predict additional costs that the design would produce when in manufacture.

Using the authors new design life-cycle, each discipline has to pass a review gate to ensure a reduction of risk through the design life-cycle. Engineering disciplines like weight engineering and structure analysis engineering can offer this information; however manufacturing engineering has not been able to introduce tangible data in the same way prior to this research. This research offers a solution to this with the design evaluation tool measuring the manufacturability of the design during the design of the product, while enabling the lead design engineers to compare product designs, measuring how well each designer has introduced design for manufacturing to the product. To validate and test the design evaluation tool, Chapter 6 highlights how effective the tool will be when implemented into the design life-cycle within aircraft manufacture. The author uses three experimental phases to demonstrate the validation of the design evaluation tool, these are discussed in detail in Chapter 6.

7.4 Future Research

During this research, the author has faced a number of challenges from this complex research area and has identified areas in the existing knowledge base which has indicated the need for further research. Due to the complexity of this research, the author's contribution to knowledge opens up many areas of future research. Therefore the author feels it necessary to suggest the following subjects for future research:

Areas that need further research concerning the design environment:

- Development of the selection tool that not only aids the selection of the environment for the aircraft industry but expands the selection by the introduction of other product designs and organisations. Allowing a global tool that can aid other industries selection of the environment that the design should operate in.

Development of the authors design life-cycle:

- Further research that develops controls in the design life-cycle ensuring the product is being designed to the customer requirements as it progresses through each phase. As discussed in Chapter 2, in many cases a design engineer's trait is to "*over design*" rather than design to the customer requirements.
- Further research could be employed to formally control the knowledge of experienced designers within the author's structured design life-cycle process. This will answer the concerns from the author's findings in the literature search, where French (1998) claims;

"What design methods cannot do and probably never will be able to do is to replace the gifts of a talented designer, nor provide step by step instructions for the production of experienced designers"

- The author's design life-cycle would be made far more concise if the review gate process undertook further research to enable a controlled decision process in this key driver in the author's design life-cycle.
- To help make the author's complex design life-cycle useable in an industrial environment the author recommends further research to embody the design life-cycle into the current Product Data Management (PDM) tools.

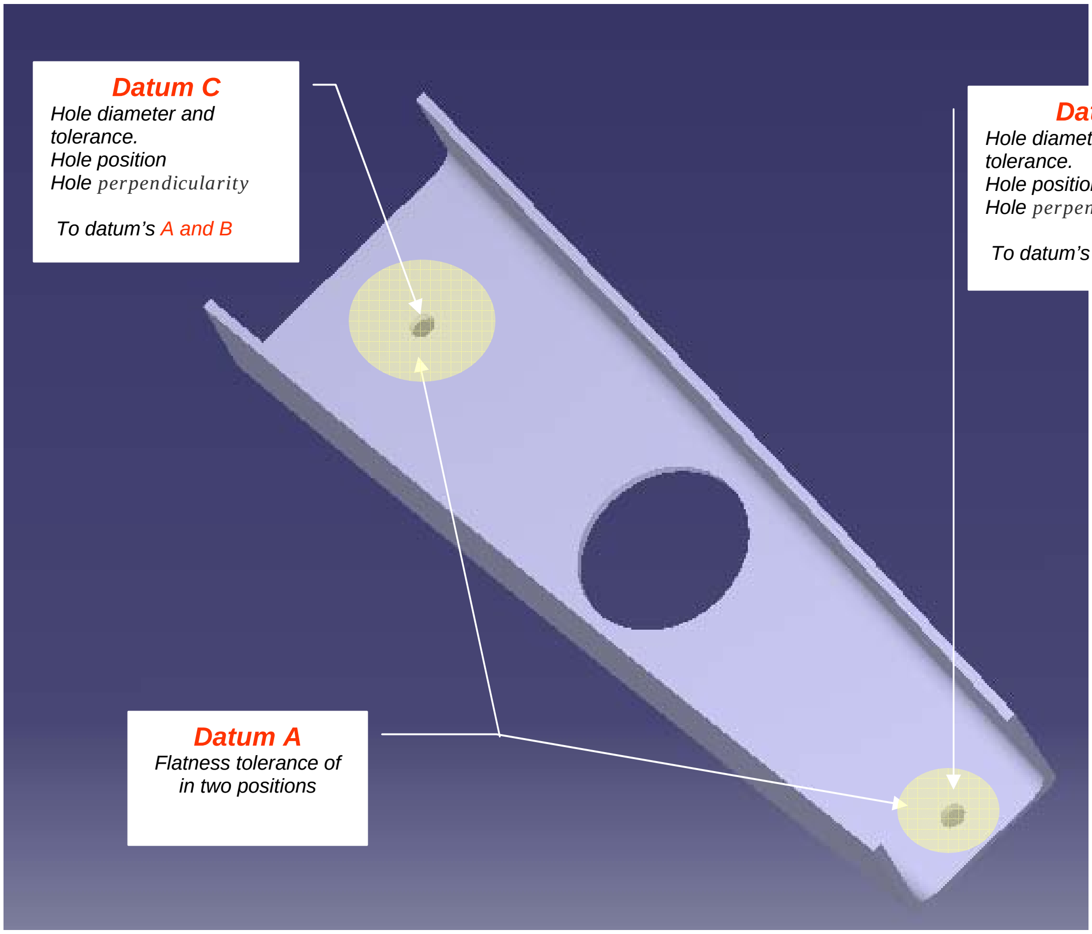
Further research into the design evaluation tool, would further the author's contribution to knowledge and enhance the following areas;

- To truly achieve a *"real time"* evaluation of a design without extending the product's life-cycle the author recommends further research into the introduction of the authors design evaluation tool into current 3D design software packages. This could be a visible calculation of the effect the design will have on the organisation when the product is being manufactured thus illustrating to the engineer how manufacturable the design is. When various features are selected by the design engineers the manufacturability will be highlighted giving the engineer a choice, ensuring a manufacturable design is achieved.
- Further research could develop the tool's features enabling a more detailed analysis of the design in areas, highlighted in the literature review; Design for X, Design for Maintainability, Design for Weight etc. This would enable a comparison of these varies areas.
- The author recommends further research work to be undertaken so the design evaluation tool could be developed to enable its use in a wider field of products and industries.

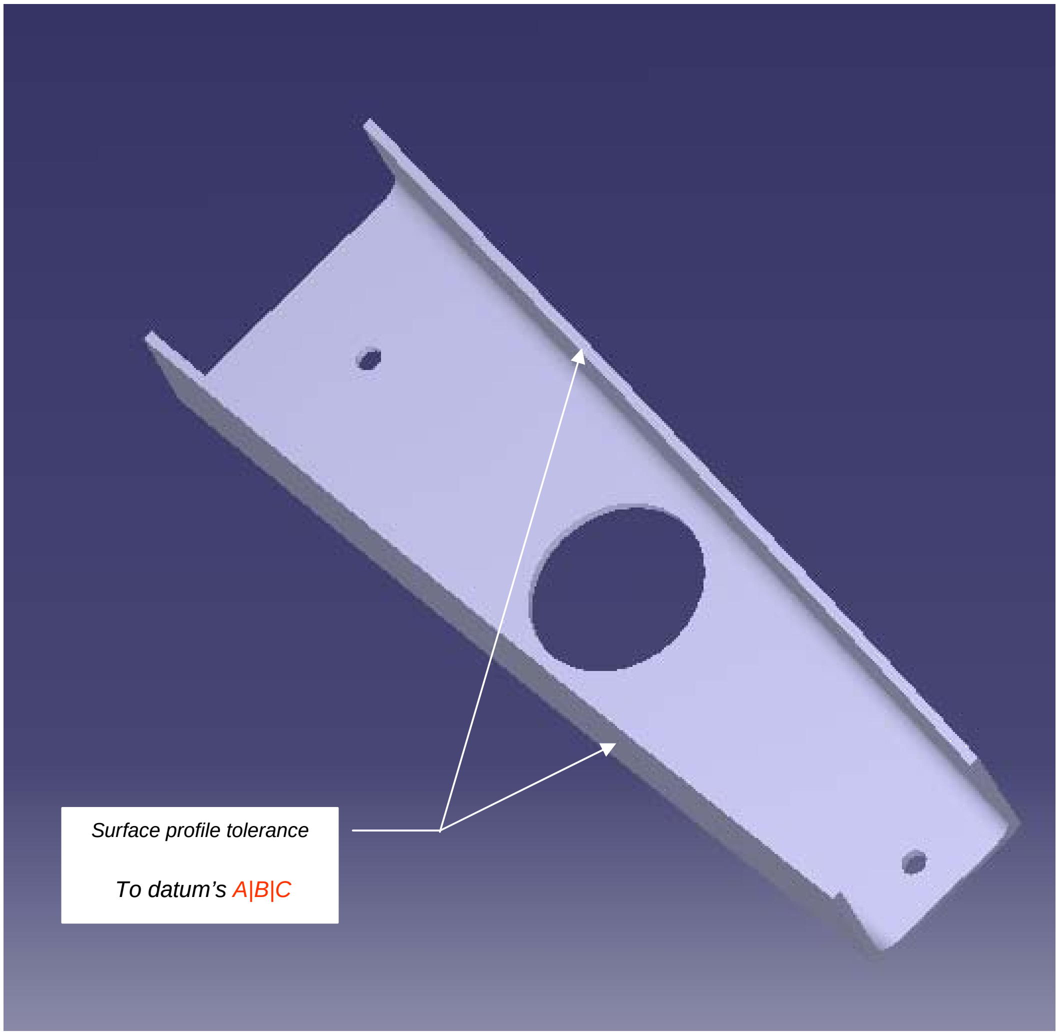
Appendices

Appendix 1

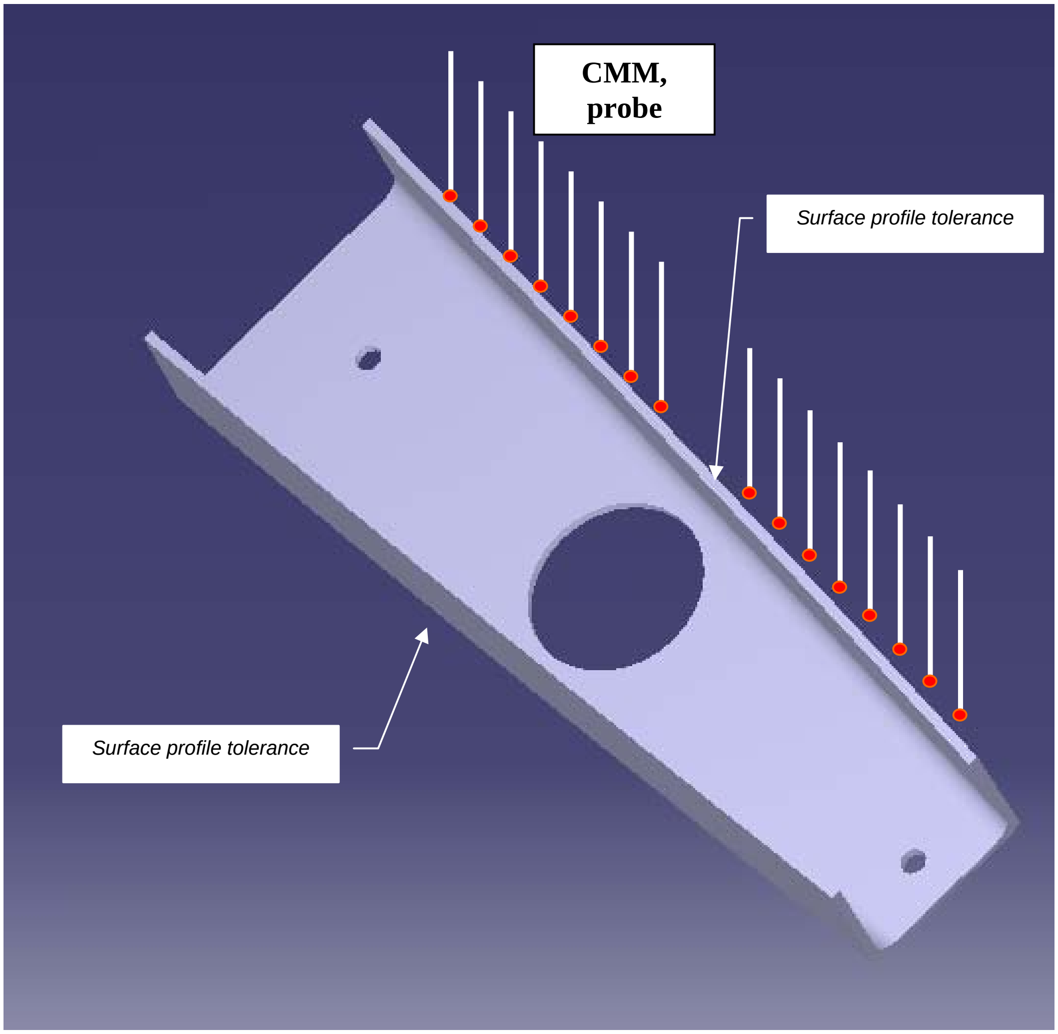
The Rib shown below is a typical example of a metallic rib, with the key features highlighted. The component may be jig located on three datum's A,B & C. The key features would have tolerances applied to them to ensure the Rib is positioned within a required envelope on assembly.



From the datum key features there can be many key features that ensure fitment on assembly. The 3D model below highlights the surface profile key feature that is controlled back to the main datum scheme.



These features are similar to those that will be used as an example throughout the calculation, Metallic rib - surface profile. The CMM machine is used to determine whether the points are within the design specification by probing the complete surface profile as illustrated below.



Appendix 2

Defect repair costs, within the design evaluation tool, for the detail components.

Feature	***Repair time (+) in Hrs***	***Repair time (-) in Hrs***
Bore Dia - General		
Machine set up	2.5	2.5
Machine Run time	0.5	0.5
Manufacture of a sleeve/bush	1	N/A
Total	**4**	**3**
Bore Perp - General		
Machine set up	2.5	2.5
Machine Run time	0.5	0.5
Manufacture of a sleeve/bush	1	1
Total	**4**	**4**
Bore Pos - General	4	4
Machine set up	2.5	2.5
Machine Run time	0.5	0.5
Manufacture of a sleeve/bush	1	1
Total	**4**	**4**
EOP - Skins Comp		
Hand Dressing	3	N/A
Total	**3**	**N/A**
EOP - Spars Comp	3	
Hand Dressing	3	N/A
Total	**3**	**N/A**
Face perp - General		0
Machine set up	1.25	N/A
Machine Run time	0.5	N/A
Total	**1.75**	**N/A**
Flatness- Rib, met		0
Machine set up	1	N/A
Machine Run time	0.1	N/A
Total	**1.1**	**N/A**
Flatness- Skin, comp		
Machine set up	1	N/A
Machine Run time	0.1	N/A
Total	**1.1**	**N/A**
Flatness- Spar, comp	1.1	0
Machine set up	1	N/A
Machine Run time	0.1	N/A
Total	**1.1**	**N/A**
Flatness- Spar, met	1.1	0
Machine set up	1	N/A
Machine Run time	0.1	N/A
Total	**1.1**	**N/A**
Hole Dia - pilot holes		

Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.5**	**0.333**
Hole Dia (drill) - Comp		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.5**	**0.333**
Hole Dia (drill) - Rib		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.5**	**0.333**
Hole Dia (drill) - Spar		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.5**	**0.333**
Hole Dia (ream) - Rib		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.583**	**0.416**
Hole Dia (ream) - Spar		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.583**	**0.416**
Hole Perp - Rib		
Open up the hole	0.5	0.5
Counterbore for bush	0.25	0.25
Fit bush	0.25	0.25
Make the bush	0.5	0.5
Total	**1.5**	**1.5**
Hole Perp - Spar		
Open up the hole	0.5	0.5
Counterbore for bush	0.25	0.25
Fit bush	0.25	0.25
Make the bush	0.5	0.5
Total	**1.5**	**1.5**
Hole Pos - Rib		
Open up the hole	0.5	0.5
Counterbore for bush	0.25	0.25
Fit bush	0.25	0.25
Make the bush	0.5	0.5

Total	**2**	**2**
Hole Pos - Spar		
Open up the hole	0.5	0.5
Counterbore for bush	0.25	0.25
Fit bush	0.25	0.25
Make the bush	0.5	0.5
Total	**2**	**2**
Skin Thickness		
Hand Dressing	1.1	N/A
Total	**1.1**	**N/A**
Surf profile - Spar, Comp		
Machine set up	1.5	N/A
Machine Run time	0.25	N/A
Total	**1.75**	**N/A**
Surface profile - Rib		
Machine set up	1.5	N/A
Machine Run time	0.25	N/A
Total	**1.75**	**N/A**
Surface profile - Spar		
Machine set up	1.5	N/A
Machine Run time	0.25	N/A
Total	**1.75**	**N/A**
WID - General		
Machine set up	1.5	N/A
Machine Run time	0.25	N/A
Total	**1.75**	**N/A**

Defect repair costs, within the design evaluation tool, for the assembly features

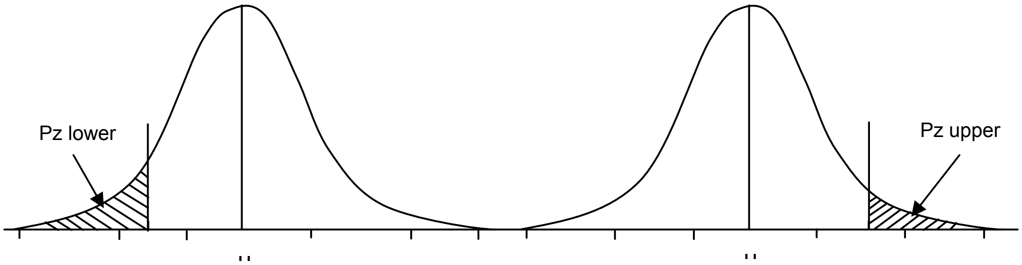
Feature	***Repair time (+) in Hrs***	***Repair time (-) in Hrs***
Anchor nut - bonded		
Removal and dressing / deburr	0.5	0.5
Re-fitting	0.25	0.25
Total	**0.75**	**0.75**
Anchor nut - riveted		
Removal and dressing / deburr	0.5	0.5
Re-fitting	0.25	0.25
Total	**0.75**	**0.75**
Assembly Machining		
Dressing / repair	2	N/A
Total	**2**	**0**
Hole Dia (drill) - Structural		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.5**	**0.333**

Hole Dia (drill) - Auto		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.5**	**0.333**
Hole Dia (ream) - Auto		
Open up the hole	0.5	0.333
Counterbore for bush	0.25	N/A
Fit bush	0.25	N/A
Make the bush	0.5	N/A
Total	**1.583**	**0.416**
Hole Pos - Structural		
Open up the hole	0.5	0.5
Counterbore for bush	0.25	0.25
Fit bush	0.25	0.25
Make the bush	0.5	0.5
Total	**2**	**2**
Jig Location of components		
Re-removal and re-assembly	0.5	0.5
Total	**0.5**	**0.5**
Part to Part location of components		
Re-removal and re-assembly	0.5	0.5
Total	**0.5**	**0.5**
Rivets - Blind		
Re-removal and re-assembly	0.5	0.5
Total	**0.5**	**0.5**
Rivets - Standard		
Re-removal and re-assembly	0.75	0.75
Total	**0.75**	**0.75**
Shimming Joints - Mouldable		
Dis-assemble	0.25	0.25
Remove shim	0.5	0.5
Re-apply shim	0.5	0.5
Re-assemble	0.25	0.25
Total	**1.5**	**1.5**
Shimming Joints - Solid		
Re-move shim	0.125	0.125
Re-apply shim	0.125	0.125
Total	**0.25**	**0.25**
Structural Gap condition		
Dis-assemble	0.25	0.25
Rework components	1	N/A
Fit shim	N/A	0.5
Re-assemble	0.25	0.25
Total	**1.5**	**1**
Two piece fasteners - manual torque		
Removal of fastner	0.25	0.25
Replace fastner	0.25	0.25
Total	**0.5**	**0.5**
Two piece fasteners - self torque		

Removal of fastner	0.25	0.25
Replace fastner	0.25	0.25
Total	**0.5**	**0.5**

Appendix 3

The table below represents the proportions under the tail of the normal distribution:



z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641
0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
0.7	0.2420	0.2389	0.2358	0.2327	0.2297	0.2266	0.2236	0.2206	0.2177	0.2148
0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
2.6	0.0046	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
2.8	0.0025	0.0024	0.0024	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019	0.0019
2.9	0.0018	0.0018	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014	0.0013

3.0	0.00135
3.1	0.0009
3.2	0.0006
3.3	0.0040
3.4	0.0030
3.5	0.00250
3.6	0.0015
3.7	0.0010
3.8	0.0007
3.9	0.0005
4.0	0.00003

Appendix 4

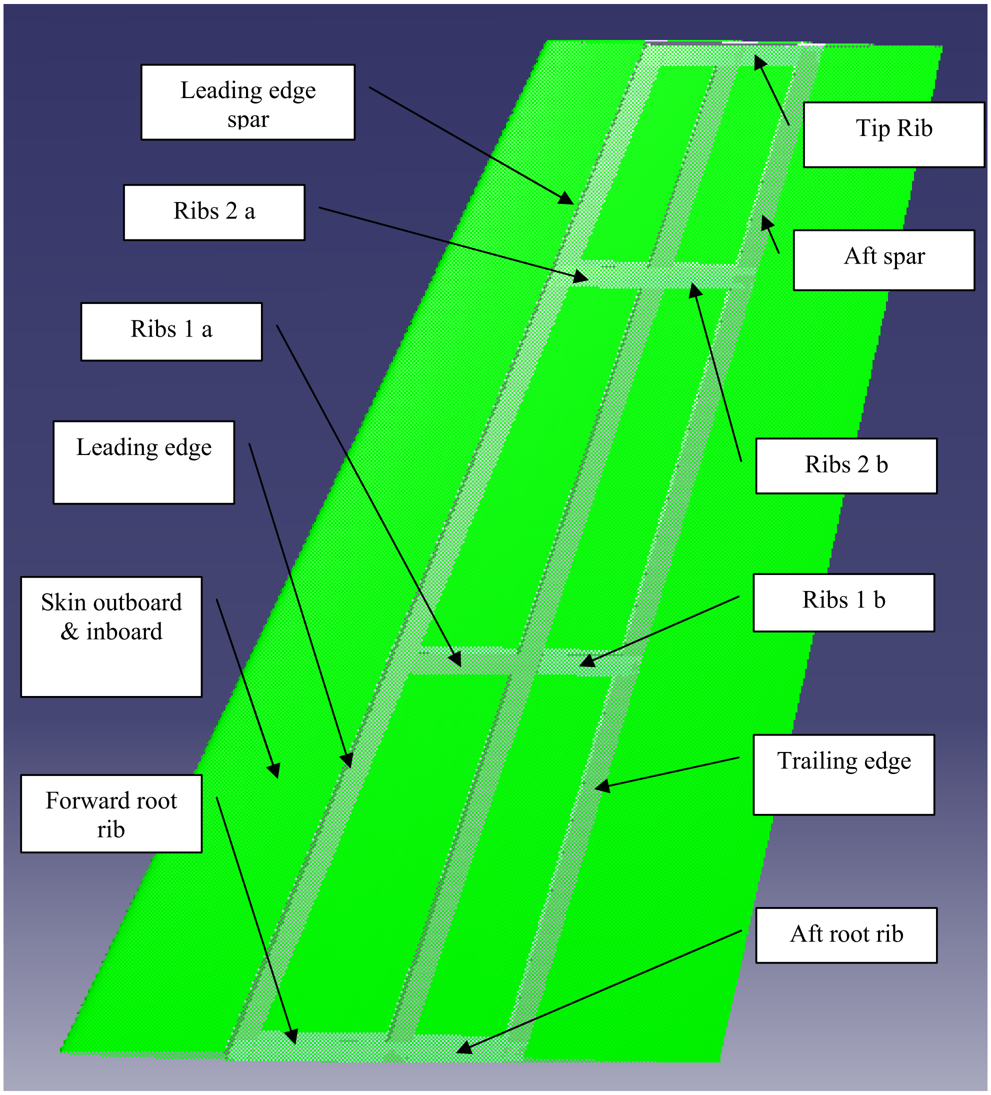
Z Value	Pz Value	12th Order Polynomial	Z Value	Pz Value	12th Order Polynomial	Z Value	Pz Value	12th Order Polynomial
0.00	0.5000	0.5000	1.00	0.1587	0.1587	2.00	0.0228	0.0228
0.01	0.4960	0.4960	1.01	0.1562	0.1563	2.01	0.0222	0.0222
0.02	0.4920	0.4920	1.02	0.1539	0.1539	2.02	0.0217	0.0217
0.03	0.4880	0.4880	1.03	0.1515	0.1515	2.03	0.0212	0.0212
0.04	0.4840	0.4840	1.04	0.1492	0.1492	2.04	0.0207	0.0207
0.05	0.4801	0.4801	1.05	0.1469	0.1469	2.05	0.0202	0.0202
0.06	0.4761	0.4761	1.06	0.1446	0.1446	2.06	0.0197	0.0197
0.07	0.4721	0.4721	1.07	0.1423	0.1423	2.07	0.0192	0.0192
0.08	0.4681	0.4681	1.08	0.1401	0.1401	2.08	0.0188	0.0188
0.09	0.4641	0.4641	1.09	0.1379	0.1379	2.09	0.0183	0.0183
0.10	0.4602	0.4602	1.10	0.1357	0.1357	2.10	0.0179	0.0179
0.11	0.4562	0.4562	1.11	0.1335	0.1335	2.11	0.0174	0.0174
0.12	0.4522	0.4522	1.12	0.1314	0.1314	2.12	0.0170	0.0170
0.13	0.4483	0.4483	1.13	0.1292	0.1292	2.13	0.0166	0.0166
0.14	0.4443	0.4443	1.14	0.1271	0.1271	2.14	0.0162	0.0162
0.15	0.4404	0.4404	1.15	0.1251	0.1251	2.15	0.0158	0.0158
0.16	0.4364	0.4364	1.16	0.1230	0.1230	2.16	0.0154	0.0154
0.17	0.4325	0.4325	1.17	0.1210	0.1210	2.17	0.0150	0.0150
0.18	0.4286	0.4286	1.18	0.1190	0.1190	2.18	0.0146	0.0146
0.19	0.4247	0.4246	1.19	0.1170	0.1170	2.19	0.0143	0.0143
0.20	0.4207	0.4207	1.20	0.1151	0.1151	2.20	0.0139	0.0139
0.21	0.4168	0.4168	1.21	0.1131	0.1131	2.21	0.0136	0.0136
0.22	0.4129	0.4129	1.22	0.1112	0.1112	2.22	0.0132	0.0132
0.23	0.4090	0.4090	1.23	0.1093	0.1093	2.23	0.0129	0.0129
0.24	0.4052	0.4052	1.24	0.1075	0.1075	2.24	0.0125	0.0125
0.25	0.4013	0.4013	1.25	0.1056	0.1056	2.25	0.0122	0.0122
0.26	0.3974	0.3974	1.26	0.1038	0.1038	2.26	0.0119	0.0119
0.27	0.3936	0.3936	1.27	0.1020	0.1020	2.27	0.0116	0.0116
0.28	0.3897	0.3897	1.28	0.1003	0.1003	2.28	0.0113	0.0113
0.29	0.3859	0.3859	1.29	0.0985	0.0985	2.29	0.0110	0.0110
0.30	0.3821	0.3821	1.30	0.0968	0.0968	2.30	0.0107	0.0107
0.31	0.3783	0.3783	1.31	0.0951	0.0951	2.31	0.0104	0.0104
0.32	0.3745	0.3745	1.32	0.0934	0.0934	2.32	0.0102	0.0102
0.33	0.3707	0.3707	1.33	0.0918	0.0918	2.33	0.0099	0.0099
0.34	0.3669	0.3669	1.34	0.0901	0.0901	2.34	0.0096	0.0096
0.35	0.3632	0.3632	1.35	0.0885	0.0885	2.35	0.0094	0.0094
0.36	0.3594	0.3594	1.36	0.0869	0.0869	2.36	0.0091	0.0091
0.37	0.3557	0.3557	1.37	0.0853	0.0853	2.37	0.0089	0.0089
0.38	0.3520	0.3520	1.38	0.0838	0.0838	2.38	0.0087	0.0086
0.39	0.3483	0.3483	1.39	0.0823	0.0823	2.39	0.0084	0.0084
0.40	0.3446	0.3446	1.40	0.0808	0.0808	2.40	0.0082	0.0082
0.41	0.3409	0.3409	1.41	0.0793	0.0793	2.41	0.0080	0.0080
0.42	0.3372	0.3372	1.42	0.0778	0.0778	2.42	0.0078	0.0078
0.43	0.3336	0.3336	1.43	0.0764	0.0764	2.43	0.0075	0.0075
0.44	0.3300	0.3300	1.44	0.0749	0.0749	2.44	0.0073	0.0073
0.45	0.3264	0.3264	1.45	0.0735	0.0735	2.45	0.0071	0.0071

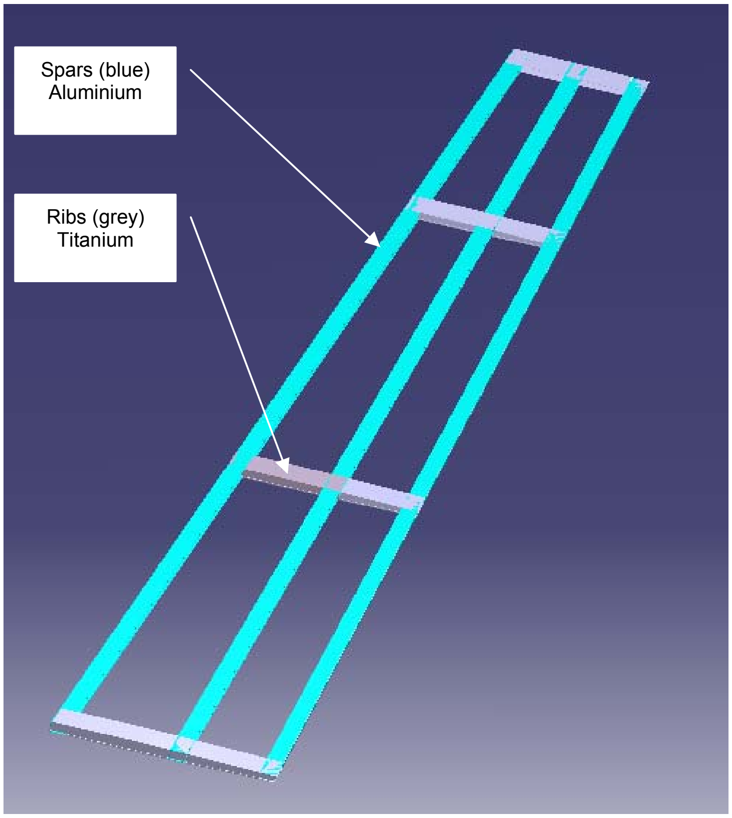
Z Value	Pz Value	12th Order Polynomial	Z Value	Pz Value	12th Order Polynomial	Z Value	Pz Value	12th Order Polynomial
0.46	0.3228	0.3228	1.46	0.0721	0.0721	2.46	0.0069	0.0069
0.47	0.3192	0.3192	1.47	0.0708	0.0708	2.47	0.0068	0.0067
0.48	0.3156	0.3156	1.48	0.0694	0.0694	2.48	0.0066	0.0066
0.49	0.3121	0.3121	1.49	0.0681	0.0681	2.49	0.0064	0.0064
0.50	0.3085	0.3085	1.50	0.0668	0.0668	2.50	0.0062	0.0062
0.51	0.3050	0.3050	1.51	0.0655	0.0655	2.51	0.0060	0.0060
0.52	0.3015	0.3015	1.52	0.0643	0.0643	2.52	0.0059	0.0059
0.53	0.2981	0.2981	1.53	0.0630	0.0630	2.53	0.0057	0.0057
0.54	0.2946	0.2946	1.54	0.0618	0.0618	2.54	0.0055	0.0055
0.55	0.2912	0.2912	1.55	0.0606	0.0606	2.55	0.0054	0.0054
0.56	0.2877	0.2877	1.56	0.0594	0.0594	2.56	0.0052	0.0052
0.57	0.2843	0.2843	1.57	0.0582	0.0582	2.57	0.0051	0.0051
0.58	0.2810	0.2810	1.58	0.0571	0.0571	2.58	0.0049	0.0049
0.59	0.2776	0.2776	1.59	0.0559	0.0559	2.59	0.0048	0.0048
0.60	0.2743	0.2743	1.60	0.0548	0.0548	2.60	0.0047	0.0047
0.61	0.2709	0.2709	1.61	0.0537	0.0537	2.61	0.0045	0.0045
0.62	0.2676	0.2676	1.62	0.0526	0.0526	2.62	0.0044	0.0044
0.63	0.2643	0.2644	1.63	0.0516	0.0516	2.63	0.0043	0.0043
0.64	0.2611	0.2611	1.64	0.0505	0.0505	2.64	0.0041	0.0041
0.65	0.2578	0.2579	1.65	0.0495	0.0495	2.65	0.0040	0.0040
0.66	0.2546	0.2546	1.66	0.0485	0.0485	2.66	0.0039	0.0039
0.67	0.2514	0.2514	1.67	0.0475	0.0475	2.67	0.0038	0.0038
0.68	0.2483	0.2483	1.68	0.0465	0.0465	2.68	0.0037	0.0037
0.69	0.2451	0.2451	1.69	0.0455	0.0455	2.69	0.0036	0.0036
0.70	0.2420	0.2420	1.70	0.0446	0.0446	2.70	0.0035	0.0035
0.71	0.2389	0.2389	1.71	0.0436	0.0436	2.71	0.0034	0.0034
0.72	0.2358	0.2358	1.72	0.0427	0.0427	2.72	0.0033	0.0033
0.73	0.2327	0.2327	1.73	0.0418	0.0418	2.73	0.0032	0.0032
0.74	0.2297	0.2297	1.74	0.0409	0.0409	2.74	0.0031	0.0031
0.75	0.2266	0.2266	1.75	0.0401	0.0401	2.75	0.0030	0.0030
0.76	0.2236	0.2236	1.76	0.0392	0.0392	2.76	0.0029	0.0029
0.77	0.2206	0.2207	1.77	0.0384	0.0384	2.77	0.0028	0.0028
0.78	0.2177	0.2177	1.78	0.0375	0.0375	2.78	0.0027	0.0027
0.79	0.2148	0.2148	1.79	0.0367	0.0367	2.79	0.0026	0.0026
0.80	0.2119	0.2119	1.80	0.0359	0.0359	2.80	0.0026	0.0026
0.81	0.2090	0.2090	1.81	0.0351	0.0352	2.81	0.0025	0.0025
0.82	0.2061	0.2061	1.82	0.0344	0.0344	2.82	0.0024	0.0024
0.83	0.2033	0.2033	1.83	0.0336	0.0336	2.83	0.0023	0.0023
0.84	0.2005	0.2005	1.84	0.0329	0.0329	2.84	0.0023	0.0023
0.85	0.1977	0.1977	1.85	0.0322	0.0322	2.85	0.0022	0.0022
0.86	0.1949	0.1949	1.86	0.0314	0.0315	2.86	0.0021	0.0021
0.87	0.1922	0.1922	1.87	0.0307	0.0307	2.87	0.0021	0.0021
0.88	0.1894	0.1894	1.88	0.0301	0.0301	2.88	0.0020	0.0020
0.89	0.1867	0.1867	1.89	0.0294	0.0294	2.89	0.0019	0.0019
0.90	0.1841	0.1841	1.90	0.0287	0.0287	2.90	0.0019	0.0019
0.91	0.1814	0.1814	1.91	0.0281	0.0281	2.91	0.0018	0.0018
0.92	0.1788	0.1788	1.92	0.0274	0.0274	2.92	0.0018	0.0018
0.93	0.1762	0.1762	1.93	0.0268	0.0268	2.93	0.0017	0.0017
0.94	0.1736	0.1736	1.94	0.0262	0.0262	2.94	0.0016	0.0016

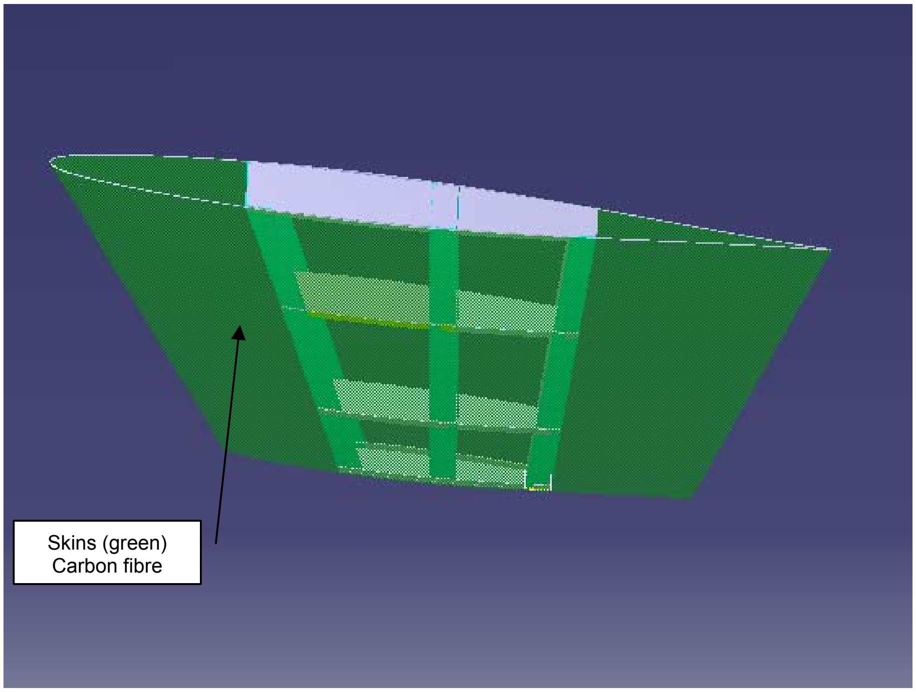
Z Value	Pz Value	12th Order Polynomial	Z Value	Pz Value	12th Order Polynomial	Z Value	Pz Value	12th Order Polynomial
0.95	0.1711	0.1711	1.95	0.0256	0.0256	2.95	0.0016	0.0016
0.96	0.1685	0.1685	1.96	0.0250	0.0250	2.96	0.0016	0.0015
0.97	0.1660	0.1660	1.97	0.0244	0.0244	2.97	0.0015	0.0015
0.98	0.1635	0.1635	1.98	0.0239	0.0239	2.98	0.0014	0.0014
0.99	0.1611	0.1611	1.99	0.0233	0.0233	2.99	0.0014	0.0014
						3.00	0.00135	0.0013
						3.50	0.00023	0.0002
						4.00	0.00003	0.0000

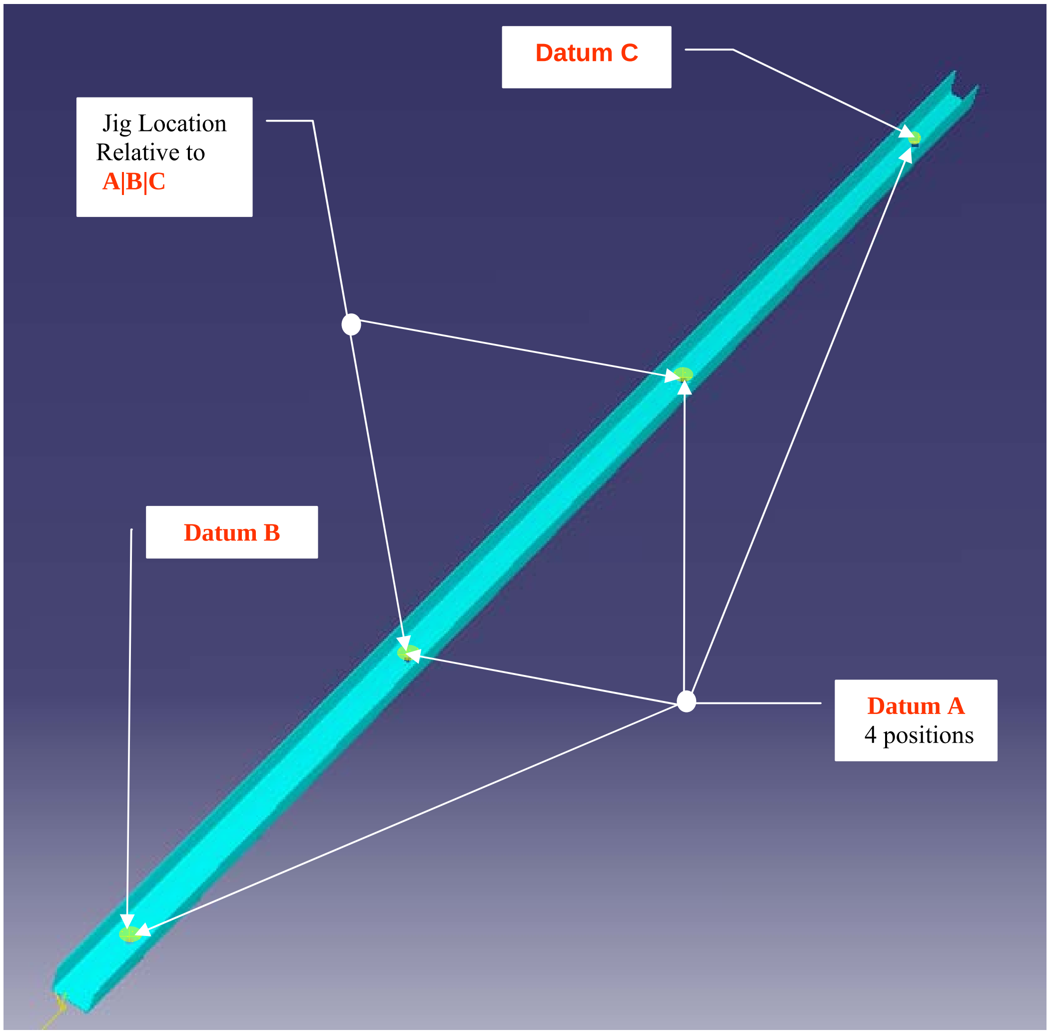
Appendix 5

The detail of the theoretical design used in experimental phase 1, chapter 6 is highlighted in this appendix. The computer aided design diagrams show the different components of the assembled structure.




Spars (blue)
Aluminium
Ribs (grey)
Titanium

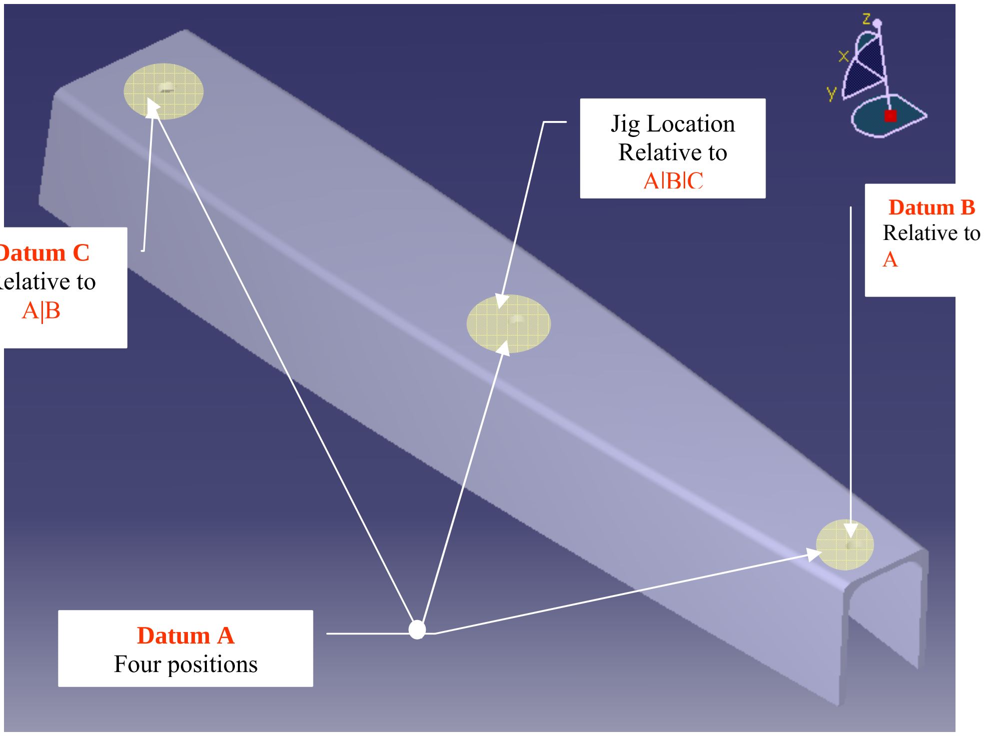

Skins (green)
Carbon fibre



The interface areas shown are typical of the spars on the product:

- Leading edge
- Mid Spar
- Aft Spar.

Each of the above features, along with the addition interfacing features, will be defined as key characteristics. The tolerances should be carefully set as they are a major factor to the assembly of the product.



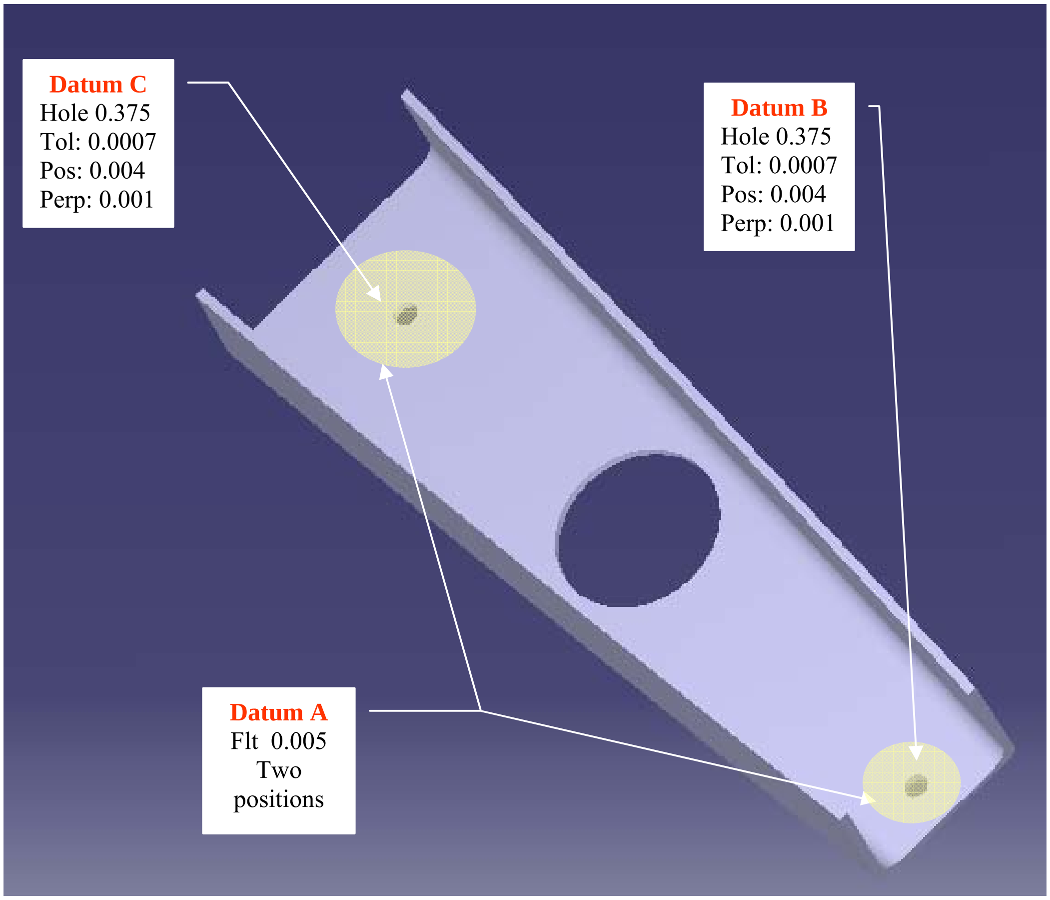
The interface areas shown are typical of the following ribs:

Tip Rib

Forward Root Rib

Aft Root Rib.

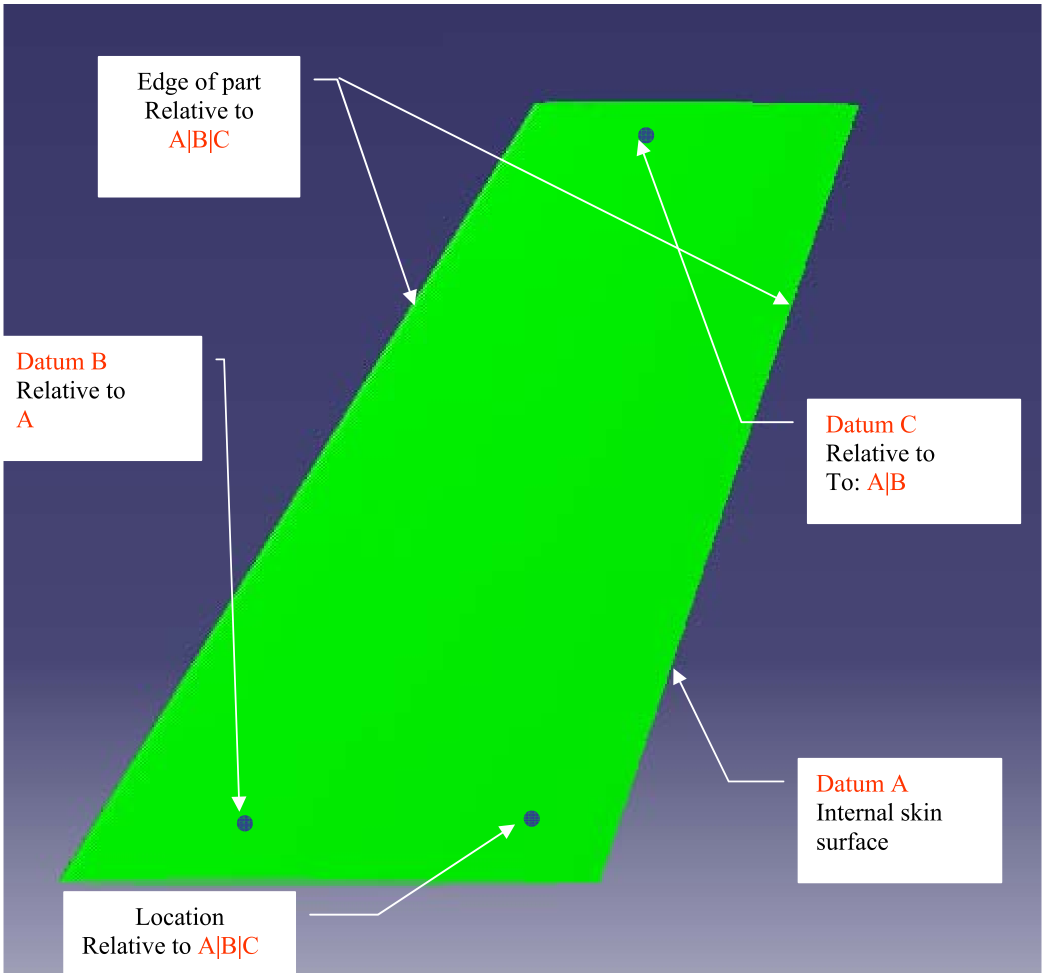
Each of the above features, along with the addition interfacing features, will be defined as key characteristics. The tolerances should be carefully set as they are a major factor to the assembly of the product.



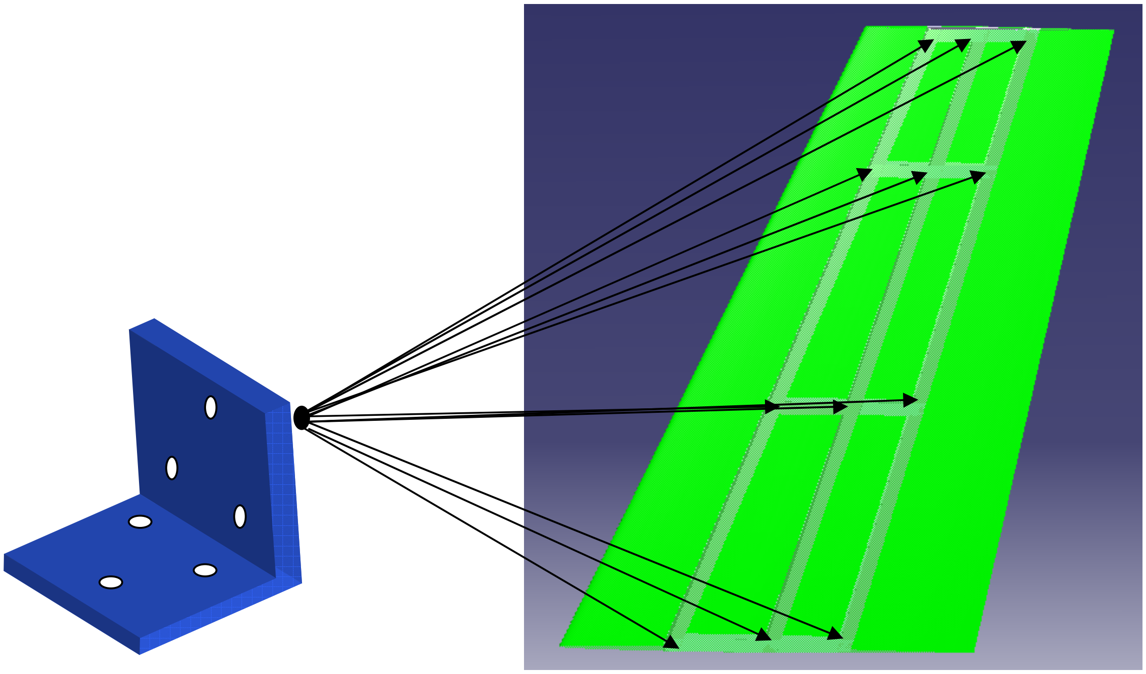
The datum scheme shown is typical of the following ribs on the product:

Rib 1 a
Rib 1 b
Rib 2 a
Rib 2 b

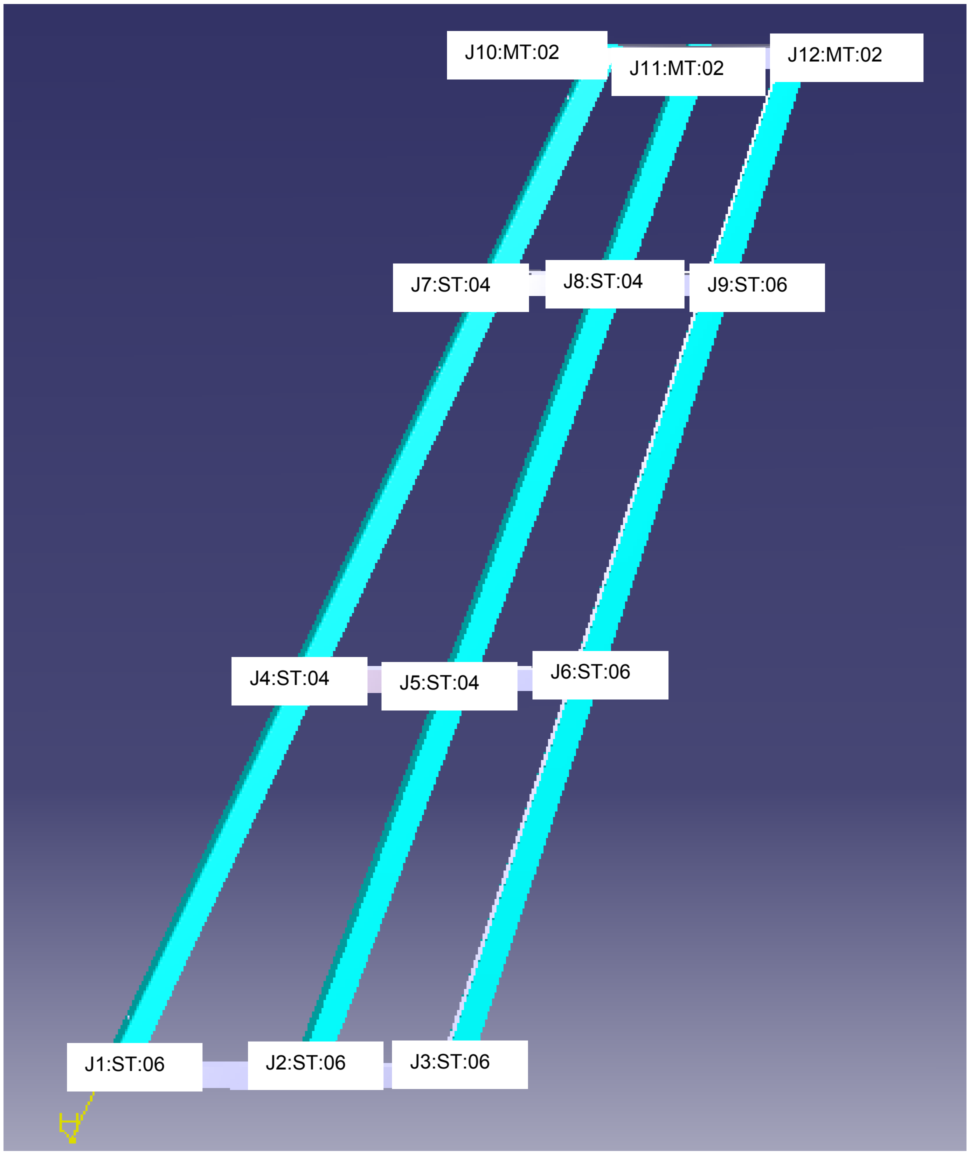
Each of the above features, along with the addition interfacing features, will be defined as key characteristics. The tolerances should be carefully set as they are a major factor to the assembly of the product.



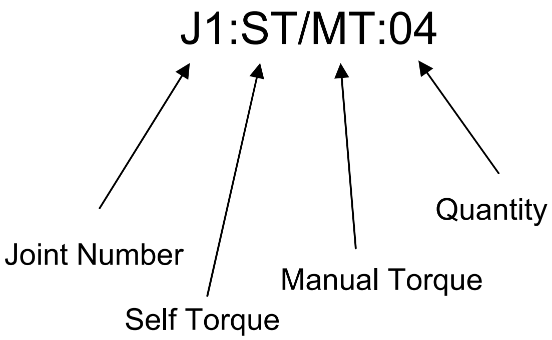
The skins will be located on selected skin attachment holes and the inside surface, these will form the datum's A,B & C. The tolerances will have to be selected to ensure the skins are positioned within a required envelope ensuring correct location in the assembly.

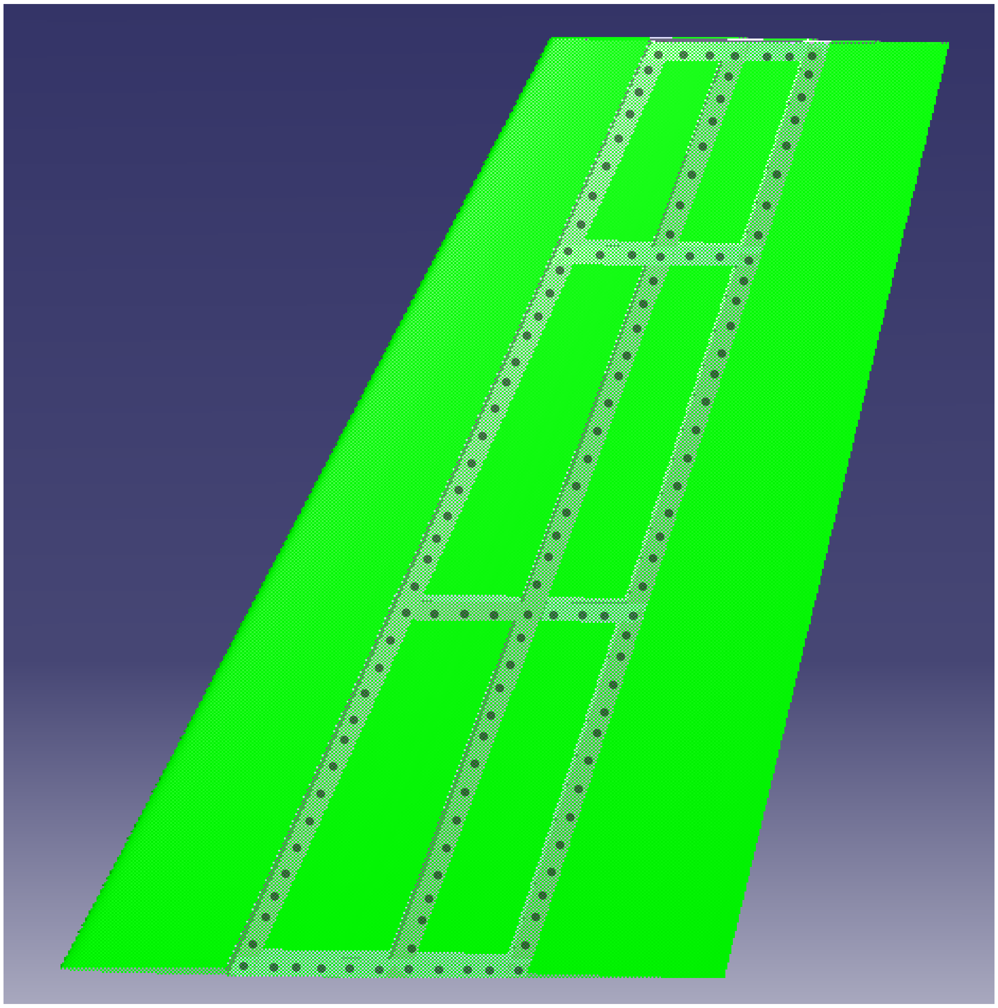


Each joint is secured with an attachment bracket as illustrated above.



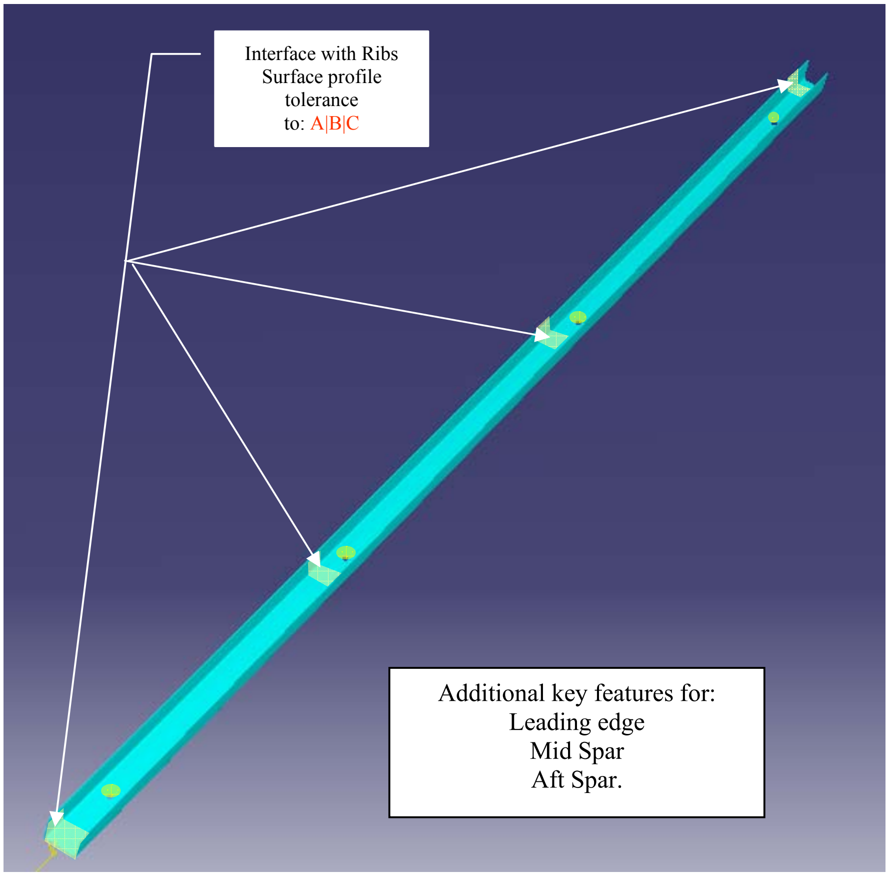
The fastener location and quantity are highlighted

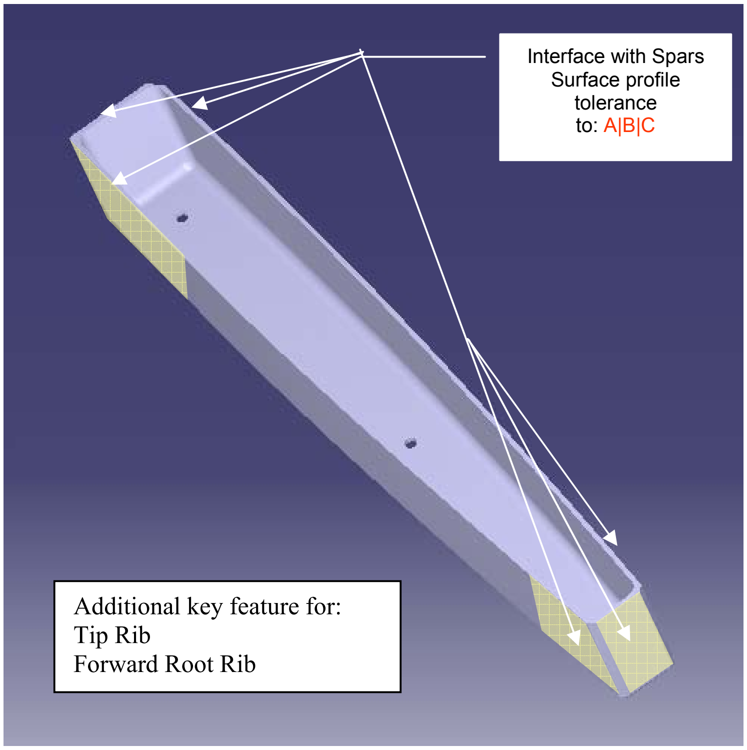




Above, highlights the fasteners between the substructure and the skins.

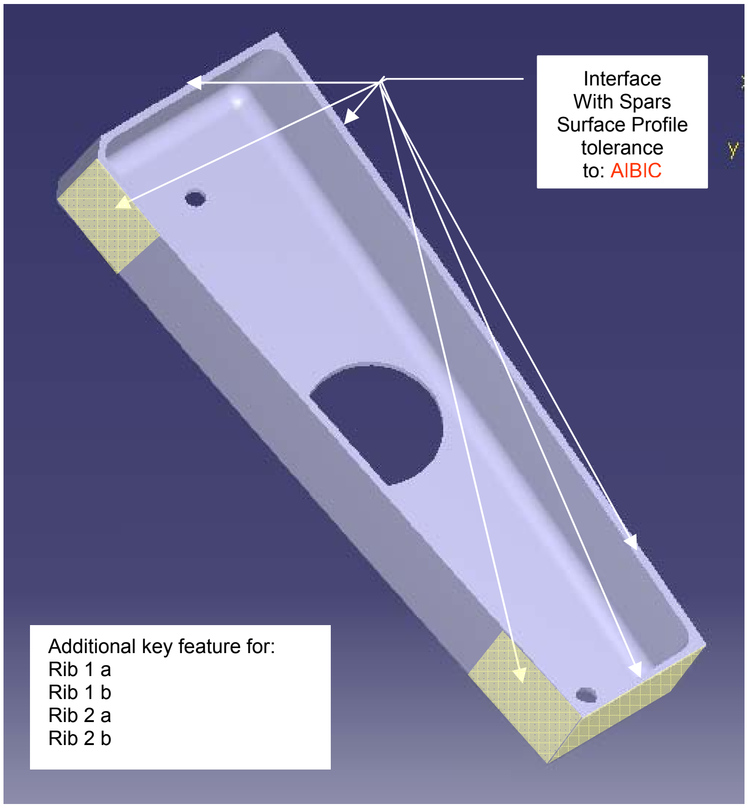
Changes to the substructure components due to trade study 2. Additional key features have been added to the parts to enable omission of the joint brackets and the introduction of integrated feature on the parts to ensure structural joints are maintained.





Interface with Spars
Surface profile
tolerance
to: A|B|C

Additional key feature for:
Tip Rib
Forward Root Rib



Interface
With Spars
Surface Profile
tolerance
to: AIBIC

Additional key feature for:
Rib 1 a
Rib 1 b
Rib 2 a
Rib 2 b

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