CRANFIELD UNIVERSITY

ANGELA WHITESIDE

DEVELOPING A CURRENT CAPABILITY DESIGN FOR MANUFACTURE FRAMEWORK IN THE AEROSPACE INDUSTRY

SCHOOL OF APPLIED SCIENCES

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ABSTRACT

Keywords: Design for Manufacture and Assembly, Process Capability Analysis

During progressive product design and development in the aerospace industry, a lack of effective communication between the sequential functions of design, manufacturing and assembly causes delays and setbacks whereby production capabilities are unable to realise design intent in high-complexity product models. There is a need to formalise the progressive design and release of an engineering model to production functions during New Product Introduction (NPI) via defining key stages of definition maturity and information requirements through a structured process.

This research develops a framework to facilitate optimal Design for Manufacture and Assembly (DfMA) based on current manufacturing capabilities within the aerospace industry, promoting effective knowledge management at all stages of design definition. The framework was developed through the accomplishment of a series of objectives: (1) Investigate optimal DfMA principles and process capability analysis through a comprehensive literature review, (2) capture the current practice of progressive drawing release in the aerospace and automotive sectors, (3) create a route map of the release process built around the optimal critical path, (4) define roles and procedures to follow at each stage and (5) validate the proposed process framework through expert opinion. These objectives were achieved through the adoption of a four-stage qualitative methodology.

The framework promotes the understanding and identification of the major stages, activities, responsibilities and information requirements throughout a structured design release process where quantified manufacturing capability data is incorporated within early design definition activities. Adherence to the process route-map ensures that no engineering model is released that cannot be realised by manufacturing and assembly functions. This facilitates the efficient organisation of information on an optimal concurrent engineering platform, leading to a reduction in product development lead-times and re-work through informed design.

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LIST OF ACRONYMS

CAPP	Computer Aided Process Planning
Cp	Process Capability
DEM	Definitive Engineering Model
DfA	Design for Assembly
DfC	Design for Control
DfLC	Design for LifeCycle
DfM	Design for Manufacture
DfMA	Design for Manufacture and Assembly
DfMt	Design for Maintenance
DfX	Design for 'X'
DfPE	Design For Process Excellence
FBH	Front Bearing Housing
FMEA	Failure Mode Effect Analysis
GQP	Global Quality Procedure
IPT	Integrated Project Team
LOP	Local Operating Procedure
MOD	Modification
MR	Manufacturing Readiness
NPI	New Product Introduction
PLM	Product Lifecycle Management
QFD	Quality Function Deployment
S/C	Supply Chain
SCU	Supply Chain Unit
SPC	Statistical Process Control

1 INTRODUCTION

1.1 Background

The aerospace industry today faces growing pressures from increased global competition, rising fuel costs and greater emphasis on environmental impact and efficiency within marketing and corporate strategy. Profit margins are tightening, and thus it is imperative to adopt efficient process planning and lean methodologies to streamline product development and minimise waste.

An aircraft engine can contain in excess of ten thousand separate components, each of which play a unique role and function in the operation and performance of that engine. Each component is defined by a series of features that determine the component shape and functionality. Due to the high complexity and sensitivity of aircraft engine design, a progressive design release process is followed during the introduction of a new product. The nature of staged product definition is built around resource planning to allow long lead-time activities such as material sourcing and machining acquisition to take place before the small details of design are finalised. Design and manufacturing functions need to communicate and negotiate on a multitude of design factors to ensure that the product can be manufactured to the desired specifications under strict quality control. This is a key Design for Manufacture and Assembly (DfMA) principle.

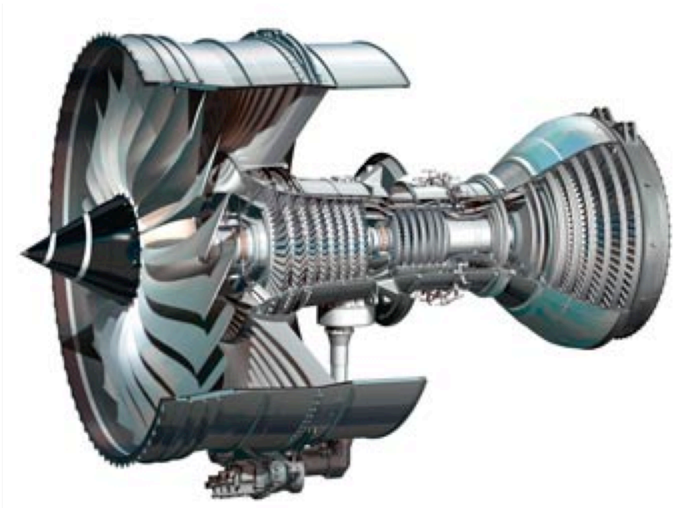

Figure 1.1: *The Trent XWB- optimised for the Airbus A350 XWB family. Adopted from www.rolls-royce.com/civil_aerospace/products/airlines/trentng/default.jsp*

On a model, design and definition functions specify the dimensional measurements required for each parameter. Due to unavoidable common cause variation in manufacturing processes caused by machine, material and human factors, it is necessary to define a variance band around the optimal value. Upper and lower specification limits define the maximum amount that the parameter in question can deviate from the optimum value with an acceptable loss in performance or functionality.

These ranges are known as tolerances, and form the key manifestation of product (design) and process (manufacturing) requirements. Design functions must ensure that the assigned tolerances adequately reflect manufacturing capabilities to produce the component to the required specification and quality. The negotiations that take place between design and manufacturing are referred to as 'buy-offs', whereby the teams collaborate and agree on a tolerance that meets both product and process requirements. This is only achieved through the promotion of a concurrent engineering environment.

1.2 Research Motivation

Miles and Swift (1998) identify that up to 80% of product costs are defined during early concept design. Despite this statistic, the design function within manufacturing organisations often sits largely unconnected to sequential functions throughout the duration of a design definition. There is often a lack of formal buy-off procedures, with manufacturing and assembly functions frequently missing a quantitative means of conveying their capabilities to design via statistical analysis and key performance indicators.

Consequently, as continued by Miles and Swift (1998), up to 50% of development effort can be wasted simply correcting product designs that have been sent back as unworkable from the manufacturing and assembly functions. There is great potential for cost and time savings in reducing the need for design iterations and concessions by improving capability knowledge sharing between company functions. Rolls-Royce, in supporting this research, have acknowledged a need to better capture current manufacturing capabilities in order to aid the design and delivery of a high quality, low defect product and reduce lead-time in support of a lean production system.

1.3 Problem Statement

A shortage of quantitative information and explicit knowledge surrounding manufacturing and assembly capabilities, coupled with a lack of structure and planning of design releases during product development, often leads to problems in successfully buying-off a design feature during a progressive model release. In order to ensure that no model is released that cannot be realised by the manufacturing and assembly functions, a structured process defining key activities and responsibilities for the progressive release procedure is required.

1.4 Project Scope

The scope of this project is contained around the integration of optimal DfMA practices within a defined and tangible process framework for the sponsoring company. This is achieved through:

- A comprehensive literature assessment surrounding the top-level principles of DfMA and process capability analysis;
- A modest benchmarking analysis of current design release practice across a sample of companies from the automotive and aerospace sectors;
- A series of interviews and workshops with 30 individuals across product introduction functions within the sponsoring company;
- A focus on three case-study component production plants around which to build the solution and undertake further interviews and workshops.

The resultant framework is designed for generic applicability across different business functions, and is not tailored around a specific application. The scope of the project does not include any in-depth, quantitative benchmarking comparisons, nor does it permit study of practices used outside the aerospace and automotive sectors. Whilst emphasising the importance of quantified process capability knowledge, an in-depth assessment into methods of statistical process control and robust design is deemed out of scope.

1.5 Company Overview

'Trusted to Deliver Excellence'

Rolls-Royce plc. is the second largest aircraft engine manufacturer in the world, operating within four global markets - civil aerospace, defence aerospace, energy and marine. A truly global company, Rolls-Royce employs 38,000 people and manufactures from 20 difference countries, serving customers in 150 countries. The success and growth of this British company is achieved via its constant emphasis on providing unrivalled, all-encompassing and high-quality service and aftercare to the consumer.

By leading the manufacturing movement from simple product provision towards an extensive service package throughout the product lifetime, Rolls-Royce has built up a vast and trusted customer base comprising of over 600 airlines, 4,000 corporate and utility aircraft and helicopter operators, 160 armed forces and more than 2,000 marine customers including 70 navies. Annual sales total £7.4 billion, 53% of which are services revenues. Rolls-Royce place significant emphasis on their manufacturing capabilities; a key attributer to their success. A great deal of investment and training as part of a constant initiative to stay ahead of the standard in production and quality capabilities is the key facilitator for the quality, top-of-the-market services that they provide.

1.6 Aim and Objectives

1.6.1 Aim

The principle aim of this research is to develop a framework to facilitate optimal 'design for manufacture' based on current manufacturing capabilities within the aerospace industry. This will promote optimal concurrent engineering practice and effective knowledge management at all stages of design definition.

1.6.2 Objectives

The specific objectives of the project are to:

- Investigate optimal DfMA principles and process capability analysis through a comprehensive literature review;
- Capture the current practice of progressive drawing release in the aerospace and automotive sectors;
- Create a route map of the release process built around the optimal critical path;
- Define roles and procedures to follow at each process stage;
- Validate the proposed process framework through expert opinion.

1.7 Thesis Structure

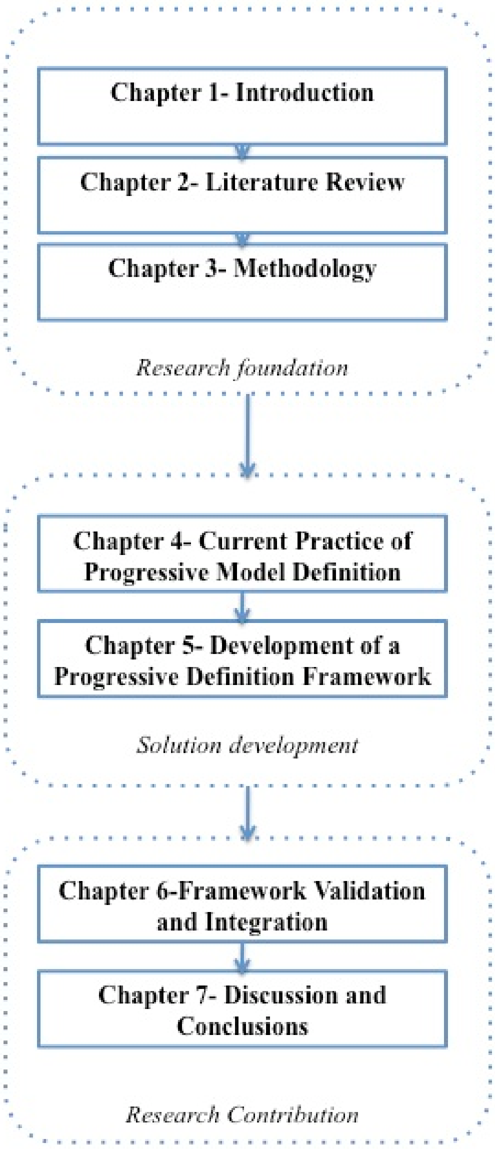

Figure 1.2: *Thesis Structure*

Figure 1.2 shows the structure of this thesis. The first three chapters build a foundation on which to commence research. Chapter 1 provides an introduction to the topic area and problem statement posed by the sponsoring company, defining the aims and objectives of the project. Chapter 2 presents a comprehensive literature review undertaken to evaluate the related research field within the wider academic and industrial environment. Chapter 3 then defines the methodology and work structure adopted throughout the duration of the research term in order to effectively answer the problem statement and develop the solution framework.

The next two chapters describe the active stages of information capture and analysis required to build and develop the solution itself. Chapter 4 details the research undertaken to assess the current practice of progressive model definition and identify the solution requirements. Chapter 5 then extends to describe the development of the process route-map itself. Chapters 6 and 7 conclude the research project by finalising the deliverable through detailed validation and integration into company procedures (chapter 6), before evaluating the findings of the study (chapter 7).

1.8 Chapter Summary

This opening chapter has presented an introduction to the research project detailed within this thesis. A background to the topic area of Design for Manufacture and Assembly throughout a progressive design release is described, identifying the motivation for further investigation and describing the specific problem statement at hand. Rolls-Royce, the sponsoring company, is introduced and the specific aims and objectives of the study are stated.

To conclude the chapter, the structure of this thesis is consolidated and the layout described. The thesis consists of seven chapters, and now proceeds onto the literature review chapter that details the wider research field, previous research and case studies carried out both in academia and within industrial context.

2 LITERATURE REVIEW

2.1 Introduction

In order to address the problem statement and formulate a current capability 'design for manufacture' process framework, the task must be set in context through a comprehension of the wider research field. This chapter provides a comprehensive literature review concerning the key research themes of Design for Manufacture and Assembly and process capability analysis. Such a review highlights the key considerations to be taken into account when establishing a new initiative.

The structure of the literature review chapter is broken down in to eight sub-sections, as outlined in Figure 2.1. Sections 2.2 and 2.3 respectively introduce the key topic areas of DfMA and New Product Introduction (NPI). Section 2.4 covers the concept of design rules and feature-based categorisation within the design process and section 2.5 details the optimal methods for defining and implementing such frameworks within an organisation.

Quantifying manufacturing capability knowledge is a principle requirement in any informed design initiative. Section 2.6 investigates the concepts of process capability and measurement, with section 2.7 discussing the definition of key characteristics and critical features within design. To conclude, section 2.8 summarises and evaluates the key themes and points identified throughout the literature review relevant to the research brief. A number of knowledge gaps are identified, namely concerning the lack of coupling between DfMA frameworks and the timely feed-in of quantified process capability information.

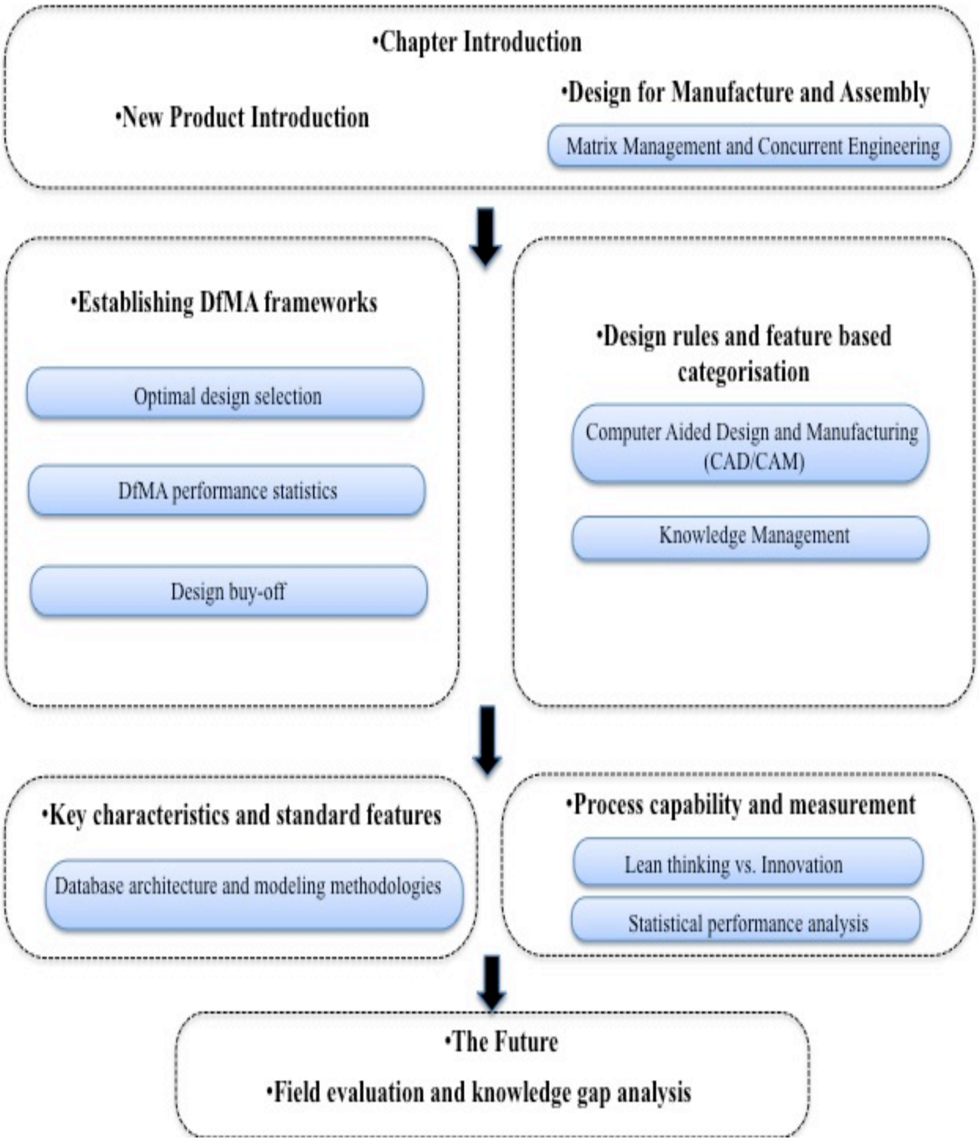

Figure 2.1: *Literature Review structure*

2.2 Design for Manufacture and Assembly

As noted by Keys (1988), the historical approach to engineering design and product development has largely been via a series of sequential stages. Firstly, a need for a new or adapted product is identified and an initial design is formulated. This is then passed to manufacturing and assembly who have the responsibility to make and build the product. It is then released onto the market, where its in-service performance, lifespan and success are determined.

However, in line with increasing product and business complexity, many industrialists began to think about the design and development effort as a holistic process to delivering a successful product. Emphasis shifted towards a focus on managing all influencing and defining factors of a product's lifecycle, from the initial concept and creation stage through to development, introduction, maturity and decline. This is known as Product Lifecycle Management, or PLM, and is defined by ANSYS inc. (2008) as "a business strategy that helps companies share product data, apply common processes and leverage corporate knowledge for the development of products from conception to retirement across the extended enterprise".

The change in thinking was principally driven by the vast array of problems and inefficiencies that arose from the more tradition methods of product development. In the past, designers would create the detailed design of the product largely independently of external considerations and the capabilities of manufacturing and assembly. These functions, as Boothroyd (1994) describes, often encounter problems on account of their inability to adhere to the drawing specifications. Requests are then made for design changes that can result in considerable delays in the final product release. In addition, the later in the product design and development cycle the changes occur, the more expensive they become.

To solve this problem, a methodology was required that incorporated manufacturing and assembly capabilities into the very earliest stages of concept design. This ensures that products are designed in such a way that they can be optimally manufactured, a principle known as 'Design for Manufacture and Assembly', or DfMA. The concurrent engineering tool of DfA (Design for Assembly) was first proposed by Boothroyd and Dewhurst (1983) after undertaking a number of studies into assembly constraints caused by inefficient product design. Expanding from this, Stoll (1986) brought such considerations into the manufacturing domain with the proposal of DfM (Design for Manufacture) techniques that promoted part reduction, simplification and the formulation of manufacturing rules for design.

As profiled by Kuo et al. (2001), the topic area has expanded to include various other dimensions within the product design stage such as maintainability, quality and lifecycle management (DfMt, DfQ and DfLC). To encompass all of these considerations, such procedures are today simply referred to as DfX- Design for 'X'. In addition to the more obvious design, engineering and manufacturing resources that are available, the design of a product is also influenced by a number of corporate level considerations such as product scope, time to market, cost, logistics and the product competitive environment. QFD (Quality Function Deployment) methodologies and assessments that translate customer requirements into product requirements are used to ensure that such considerations are deployed throughout all functions involved with the development of the product, as promoted by the adoption of the PLM mindset.

2.2.1 Matrix Management and Concurrent Engineering

Miles and Swift (1998) discuss some of the reasons why the traditional functionally organised product introduction process, where separate business functions carry out their specific roles largely independently to one another, is incapable of meeting modern requirements. The sequential nature of operation often results in protracted lead times, where resources are wasted on interdepartmental communications and other non-value added activities such as correcting designs that have confronted manufacturing issues upon release. The authors also identify that customer requirements, product design and method of manufacture cannot be adequately addressed independently by marketing, engineering, and manufacturing functions due to their intrinsic linking and inter-dependencies.

Swift and Brown (2003) emphasise the need for the implementation of 'matrix management' for the successful facilitation of DfMA methodologies. This moves companies away from a vertical business layout towards a matrix layout that as well continuing to foster functional specialists also promotes cross-functional integrated product teams. Such teams are better tailored to working within PLM and a product-centric view. This concept of integrated functional teamwork is known as Concurrent Engineering. The main emphasis of a product-centered Concurrent Engineering environment lies in the communication of knowledge and information between different functional departments working on creating, developing and maintaining a quality product. Parties work together to discover the optimal design solution from all perspectives and gain a better understanding of responsive inter-dependencies and considerations.

2.3 New Product Introduction

The optimal time to introduce Concurrent Engineering practices is during New Product Introduction (NPI). As stated, Miles and Swift (1998) identify that up to 80% of the product quality and cost are committed by the end of the concept design phase, despite the actual cost of the project being very low at this point, as illustrated in Figure 2.2. Such a statistic emphasises the dominant role that designers play in setting the cost of the product. Manufacturing, who are traditionally held responsible for product cost in fact only define a minority percentage. Effective product introduction must therefore take into account all aspects of product development and lifecycle to design an efficient process right from the offset, reducing waste via minimising the need for later design iterations.

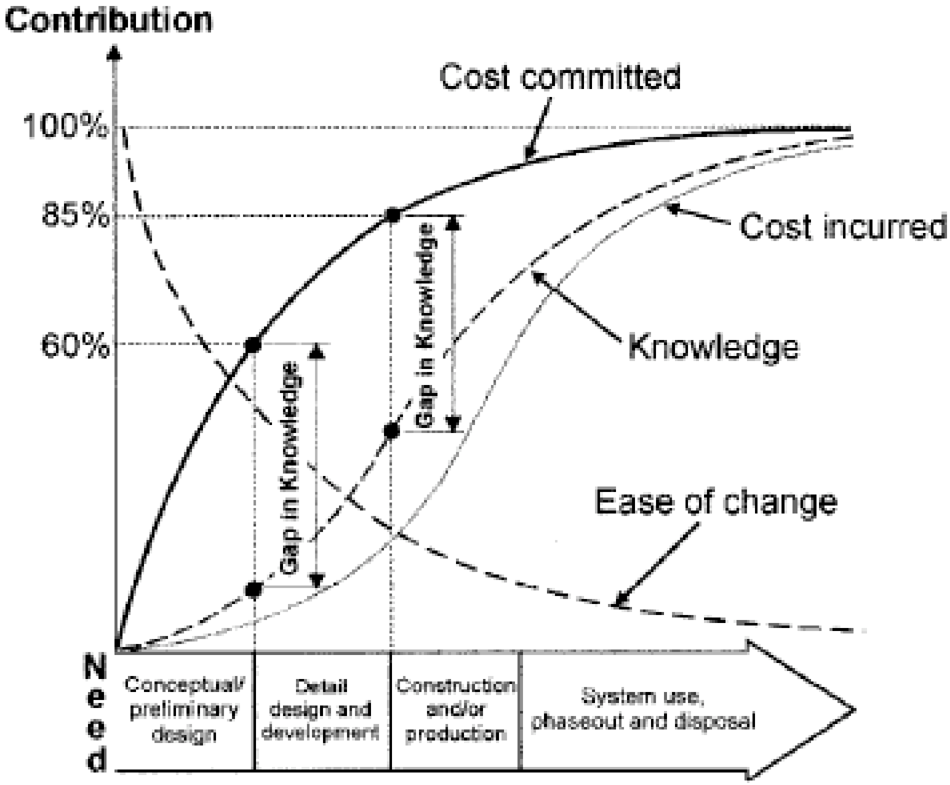

Figure 2.2: *Commitment and incursion of costs during product development. Adopted from Swift and Brown (2003)*

Such an observation is especially relevant in low-volume, high complexity and high cost manufacturing environments such as the aerospace engine industry. As highlighted by McAdam et al. (2008), NPI in the commercial aerospace industry focuses on producing lighter, greener and more efficient products that reduce operating and service costs while increasing operating performance parameters. In today's world of increasing fuel prices and environmental concerns, this has never been a more paramount concern.

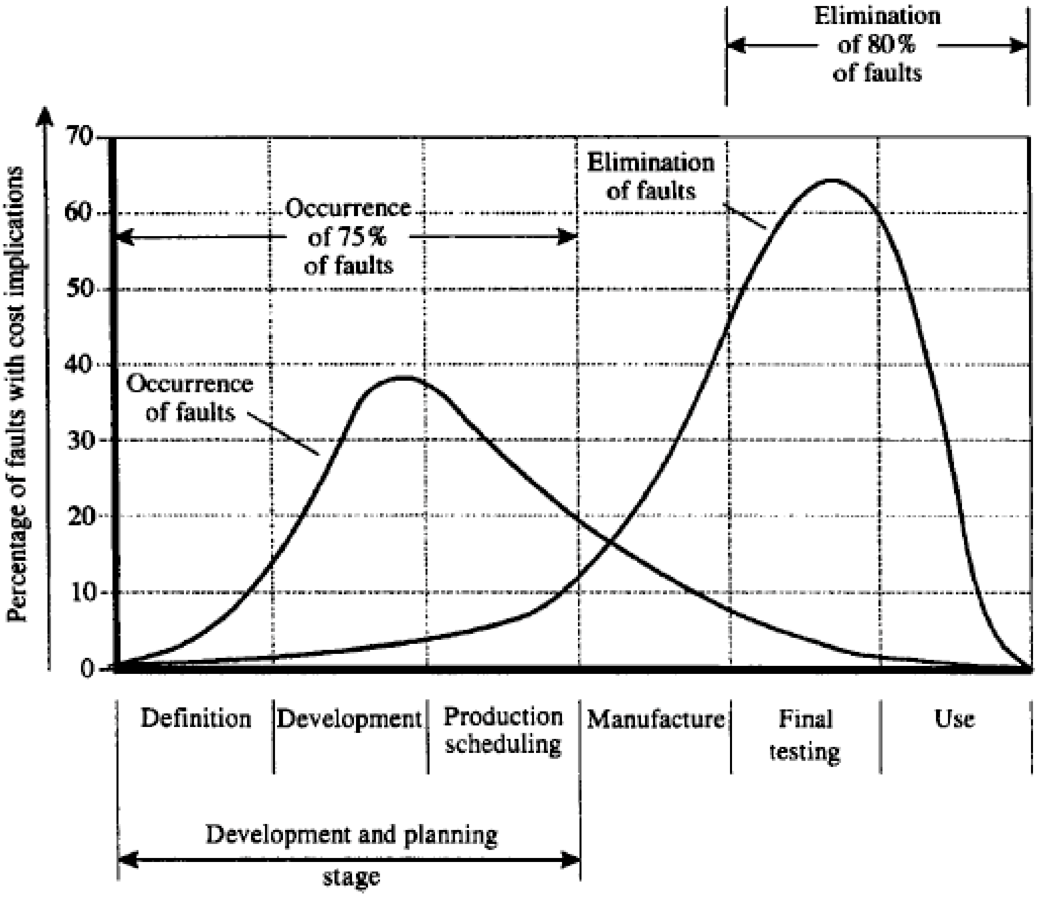

Figure 2.3: *Occurrence and elimination of faults in the product lifecycle. Adopted from Swift and Allen (1994)*

Figure 2.3 displays the discrepancy between the point of occurrence of faults and the time where they are eliminated during product introduction, demonstrating the additional costs incurred by the delay in fault correction. This is corroborated by Figure 2.4 that displays the relative proportions of rework and corrections accrued along the product introduction timescale and the reasons for that rework, which all relate back to inefficient design.

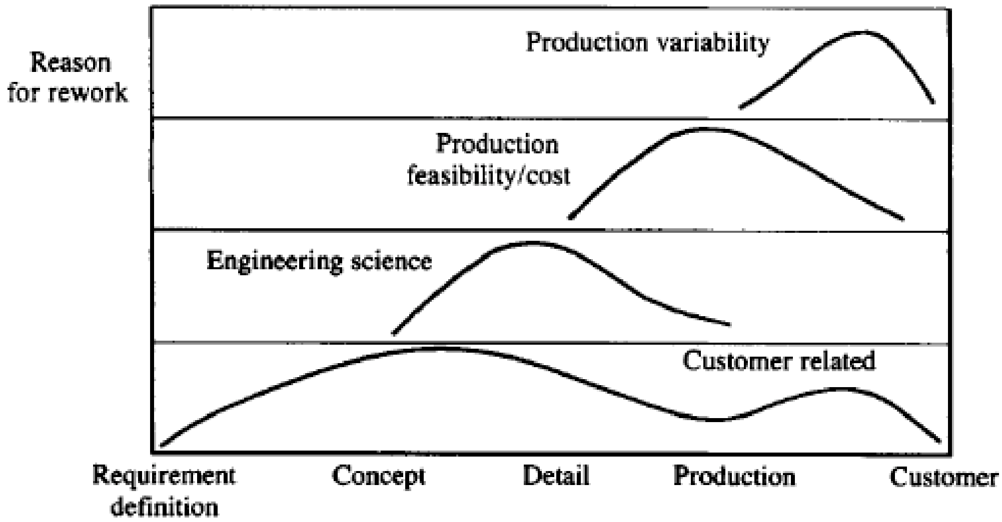

Figure 2.4: *Disposition of rework in product introduction. Adapted from Swift and (1994)*

2.4 Design Rules and Feature Based Categorisation

This notion of 'design rules' forms a substantial theme throughout DfMA literature. Miles and Swift (1998) note how the traditional approach to product design and manufacture is often based on tacit, experience-based principles and guidelines of good design practice. Although this method can prove effective in incorporating quality knowledge and information, it is inefficient on account of its informality and lack of structure and recording. There are exploitable opportunities for rationalisation and standardisation of part and procedure knowledge in order to minimise variation and promote best-practice information re-use. Such standardisation can be achieved through feature-based categorisation product modelling. Shah (1991) defines a feature as "a semantically endowed object that accompanies product development from the customer request through to product release".

In essence, the term 'feature' is a generic description that describes a prominent attribute or aspect of a product that defines functionality and has specific, attributable characteristics. The purpose of this categorisation, as explained by Hoque and Szecsi (2007), is simply to incorporate and organise known information into an accessible format. Any number and type of attributes including geometry and manufacturing process information, functionality rules and surface/joining information to assess the compatibility and interface with adjoining features can be used to identify each feature. By incorporating functionality and manufacturing rules into a feature's information set, one is ensuring from the start that the design is consistent with the functionality requirements and manufacturing capabilities.

Features can be further categorised into groups or classes. This not only aids in easier location and accessibility of specific features, but also groups together all features that are somehow similar or related by certain properties. Mechanisms can be designed to support each 'feature family', instead of special methods being supported for each feature. This permits, where appropriate, the reuse of data between related features and components, preventing unnecessary replication. As noted by Skander et al. (2007), this system also supports a better and easier to follow terminology structure and the creation of feature taxonomies, useful in developing product data exchange standards within the external supply chain.

For these reasons, many companies are making the transition towards feature-based product and process modeling. However, as emphasized by Hoque and Szesci (2007), it is important to stress that such models are not stand-alone, as they do not include other important tasks of the product development cycle such as process and assembly planning.

2.4.1 Computer Aided Design and Manufacture (CAD/CAM)

With the expansion and development of computer technology and software over the last ten years, particularly Enterprise Resource Planning (ERP) and similar collaborative tools, it is becoming easier and more common to use IT platforms for sharing information and knowledge. In addition to the more general IT platforms and software, the manufacturing industry is increasingly integrating computational facilities directly into product design and manufacture via the use of Computer Aided Design (CAD) and Computer Aided Manufacture (CAM).

Standardisations and formatting are especially relevant when considering inter-firm product design and communications within an extended supply-chain, as noted by Twigg (2002). Ford, Rover and Jaguar were the first companies to use neutral standards within CAD/CAM data exchange in the early 1980s, and since then such practices have been widely extrapolated on account of the increased ease in sharing data with customers and suppliers. According to Hoque and Szecsi (2007), many organisations have integrated DfMA information within CAD tools to the extent that designers have the ability to select features from compiled manufacturing feature libraries, and, upon insertion, the system applies all functionality and DfMA rules in real time during the actual design process. The designers can be warned or alerted if they attempt to include features that violate functionality or manufacturing rules.

Such computer aided automation techniques are gradually expanding in application across different business functions. Crow (2008) discusses that widespread focus on specific applications has lead to 'pockets' of automation within the typical organisation. Yet, with new initiatives on the horizon such as Computer Aided Process Planning (CAPP) that automates factors such as equipment selection, ordering and logistics, manufacturers are moving towards an inclusively automated design platform. By driving DfMA principles into the development of such initiatives, one moves towards a design process whereby all products are designed for optimal manufacture, assembly and performance permitted by the resources of the company.

2.4.2 Knowledge Management

In the formulation of any DfMA framework, it is of imperative performance to consider the knowledge dimension interface as well as the more obvious product and process rationalisations discussed. In addition to sources of explicit knowledge such as operating manuals, product drawings and written company procedures, employees each possess substantial tacit knowledge about their work as a result of training and experience, enabling them to fulfill their responsibilities. The key to capturing and utilising this knowledge to corporate benefit lies in finding a method to extract and record the knowledge in an efficient and organised manner so that it is available and easily-accessible to the company employees whom require it. Such a system encourages uniformity of best practice and minimises useful knowledge loss when individuals leave the company or change job role.

Cochrane et al. (2008) report on substantial research effort that has been pursued into knowledge based systems in the facilitation of capturing and representing tacit knowledge related to both the product being designed and its manufacturing environment. This knowledge can then be categorised in line with the larger DfM framework according to the defined separate product and manufacturing hierarchies. Naish (1996) identifies the importance of considering the structure and organisation of knowledge feed-in. This is to ensure that the range of knowledge input is filtered and fed in at the correct process planning stage for optimal effect. General, top-level awareness of whole process capabilities and factory capacities is used in the early, holistic views of concept assessment, whereas specific shop floor and machine level performance awareness is required for specific feature manufacturing analysis.

Edwards (2003), in a study of optimal manufacturing process identification, further emphasises this point, noting that "critical to the efficient manipulation of knowledge is the timely provision of suitable information such as materials and manufacturing processes. This information is considerable and diverse and clearly needs to be condensed and targeted to a specific design problem."

2.5 Establishing DfMA Frameworks

It is important to stress that the introduction of any DfMA framework is likely to be highly company and product specific, due to the vast difference in objectives, resources and priorities of companies across the manufacturing sector as well as the nature of the product itself. A number of academics have formulated generic staged pathways from which to approach a new DfMA procedure. TWI (2008) establishes seven key status-points in formulating a DfMA integration plan:

- **Diagnose;**

  Determinate the manufacturability of the proposed product and compare with similar products on the market

- **Set objectives;**

  Set in terms of production costs, quality, flexibility, risk, lead-time, efficiency, and environment

- **Define function;**

  Define the main functions of the product and their interactions

- **Clarify the evaluation parameters** and design ideas for each of the main product functions

- **Conceptual design** at corporate, family, structural and component levels

- **Evaluate and select;**

  Assess the manufacturability of the proposed concepts in terms of the DfM objectives. Select the best-fit concept;

- **Translate to design.**

  Communicate the chosen concept to the development team, which then carries out the detailed design in parallel to marketing and production development.

By undertaking such planning from the earliest concept stage, only optimal concepts and methodologies are taken forward to detailed development. Fabricius (1994) further the defines the four principle focus areas/activity levels to be considered at each stage:

- **Corporate level;**

  The interaction with other types of company products;

- **Family level;**

  The relationship between different variants in the same product family;

- **Structural level;**

  The relationship between the different components and subsystems;

- **Component level.**

  The design and specification of each individual component.

Such a way of top-down thinking assists in focusing at an appropriate and permitted level of granularity as the product evolves. The product introduction process, particularly in the aerospace industry, is an incredibly broad task that spans over a considerable period of time from concept to entry into service and beyond, and involves input and coordination of all business functions. As a method of systemising such a process, companies define a ‘product introduction landscape’ – a top-level diagrammatic representation of all the functional subtasks in the context of the major stages and milestones within the process. This aids in monitoring the maturity of the developing product and thus ties in well with organising information inflow according to the level of detail available at each stage.

Process design runs parallel to the evolving product design, as explained by Lu and Wood (2006), and involves understanding the characteristics of the product to determine the appropriate manufacturing techniques, capabilities and technical knowledge required to make that product to the correct specification and quality. Following the top-down approach, the process is viewed from a plan for the entire production system down to the consideration of individual processes, where more specific details such as sourcing and fixture and tool design are addressed.

2.5.1 Optimal Design Selection

Lu and Wood (2006) also note the success of the Toyota Development Process (1999) that follows the principle of Set-Based Concurrent Engineering. Designers present and share a wide set of design and process alternatives which are gradually narrowed and eliminated as the detail evolves until the final, optimal solution is found. This allows the incorporation of innovation and creative design and is largely opposed to more traditional design methodologies, where a point design solution is quickly defined and then altered and modified to meet the design objectives.

Miles and Swift (1998) propose a separation of parts into those that are demanded by the design specification and those which are required by a particular design solution. This allows one to quantify design efficiency by analysing the relative proportions of the two part types and setting particular targets for the reduction of the later via effective redesign. During functional analysis components are also classified according to their functional importance. Manufacturing analysis then draws on their knowledge base to assess the manufacturability of each part, taking into account product characteristics such as material, shape, size, complexity and finish in addition to process considerations such as achievable tolerance and production volume. This allows the consideration of alternative material and process combinations in the improvement of design efficiency.

Sohlenius' (1992) paper on Concurrent Engineering stresses the importance that the development of new generations of products and processes are not constrained by previous production process design. As McAdam et al. state (2008), design can often be restricted by the current capabilities of manufacturing equipment and supply chains if they are not updated on changes and improvements to these areas. In addition, Naish (1996) identifies the need to consider feature inter-relationships rather than just adopting a feature-by-feature planning methodology, and stresses the requirement to consider more practical geometric constraints such as tool obstruction in process planning decisions in addition to the more straightforward machining capabilities.

2.5.2 DfMA Performance Statistics

There are a number of industrial case studies detailing the successful impact of DfMA initiatives. As quoted by O'Driscoll (2001) in his paper 'Design for Manufacture', documented evidence from a number of studies into the success of DfMA implementation indicates the possibility of reducing product assembly time by up to 61%, reducing the number of assembly operations by as much as 53%, reducing 68% of assembly defects and cutting the time to market by as much as 50%.

Boothroyd Dewhurst inc. (2008) further corroborates these numbers in a study of more than 100 companies whom adopted their DfMA methodologies. Statistics indicate:

- Assembly times cut by 60%;
- Labour costs reduced by 42%;
- Product development cycle time reduced by 45%;
- Part reduction of 54%;
- Cost reduction of 50%.

Miles and Swift (1998) note that these DfM implementation statistics suggest that the applicability of DfM methods is not particularly sensitive to product type or volume, as there is little difference across the aerospace, defense, industrial and automotive business sectors.

2.5.3 Design Buy-off

As noted by Keys (1988), DfM objectives are not always possible to address and fully achieve at once with a new process and/or product due to the nature of progressive definition (particularly with high-complexity products), hence negotiations and buy-off are required as the concept progresses and more information becomes available to the integrated teams. Skander et al. (2007) discuss the pattern of progressive selection of manufacturing methods during concept design, which is largely dependant on sourcing and manufacturing lead-times and factory capacities. There is a need to incorporate regular feedback and iteration loops within the design process, particularly between the product, process and knowledge interfaces, as part of a progressive definition release.

2.6 Process Capabilities and Measurement

As quoted by the famous scientist Lord Kelvin (1824-1907), "When you can measure what you are speaking about and express it in numbers, you know something about it. Otherwise, your knowledge is a meager and unsatisfactory kind; it maybe the beginning of knowledge, but you have scarcely in thought advanced to the stage of science."

The Foundation of Manufacturing Committee of the National Academy of Engineering stress how "world-class manufacturers recognise the importance of metrics in helping to define the goals and performance expectations for the organization. They adopt or develop appropriate metrics to interpret and describe quantitatively the criteria used to measure the effectiveness of the manufacturing system and its many interrelated components".

These quotes are used by Ghalayini and Noble (1996) to set the scene well for emphasising the integral role and importance of good quality capability data and measurement information in producing quantitative performance records and metrics to drive an organisation's strategic planning and success. Today there is a constant emphasis on adopting Lean Manufacturing methods in order to remain competitive and drive product quality. Lean manufacturing, inspired by the Toyota Production System

(1992) ideology, largely focuses on streamlining production flow and improving product quality by minimising waste and variation. The elimination of waste in all its forms is the integral emphasis throughout Lean methodologies, identifying not only material waste but also time, defects and inefficiencies in the chosen manufacturing method. In today's increasingly competitive environment, there are a large number of variables within the manufacturing process that have considerable influence on cost, product performance and efficiency.

The emphasis on product quality is especially relevant given the modern day motion towards 'product servitisation' alongside the growing service sector, where, instead of selling a product, manufactures sell the service of that product. Therefore the manufacturers themselves are direct beneficiaries of improved product performance in that it lessens the cost and resources required for maintenance and servicing in addition to improving industrial standing and customer satisfaction.

2.6.1 Lean Thinking vs. Innovation

In what would appear somewhat contradictory to the Lean mentality of 'killing' variation, today's leading manufacturers also accentuate the importance of promoting an innovative culture within the organisation, driving innovation into the design and manufacturing process to identify new possibilities to improve the product. This is promoted within Set-Based Concurrent Engineering proposed by the Toyota Development System (1999) methodology, whereby the wider range of design solutions explored helps to identify new, improved ideas and capabilities. Such principles can extend to shop-floor and operational applications, as discussed by Leung and Lee, whereby machining operators and craftsmen are encouraged to actively vary and experiment with environmental conditions in order to find an optimal process method.

Bordoloia and Guerrerob (2007), as a response to this apparent contradiction between modern day emphasis on both innovative design and Lean product and process quality control, propose a new perspective - that of Design for Control (DfC). DfC places a direct focus on a design's effect on control systems, focusing on maintaining standardisation and consistency of quality during the integration or redesign of parts and products. This allows new, innovative design and manufacturing methods to be incorporated whilst still reducing uncertainty and maintaining control.

2.6.2 Statistical Performance Analysis

Within any manufacturing process, a vast amount of measurement data is collected in order to monitor and control the process and product, ensuring quality and stability. Statistical Process Control (SPC) can be used to analyse this data, measuring process capability through numerical and graphical analysis. Due to the high number of manufacturing operations and variations involved in the creation of one component, it is more practical to monitor the capability via the overall process performance as opposed to individual machining or tooling operations.

Process capability indices (PCIs), as discussed by Chang and Wu (2007), are a good means of summarising process performance relative to a set of specification limits, proving effective tools for both process capability analysis and quality assurance. The primary indices are the Cp and Cpk indices, as defined in Figure 2.5. The Cp index is a measure of the precision of a given process; the Cpk index is a measure of the distribution of points relative to the design specification limits. As a general rule across industries, a process is deemed capable if it has a Cpk of 1.33 or higher. Other Key Performance Indicators (KPIs) also provide capability indications, such as non-conformance rates and percentage of scrap.

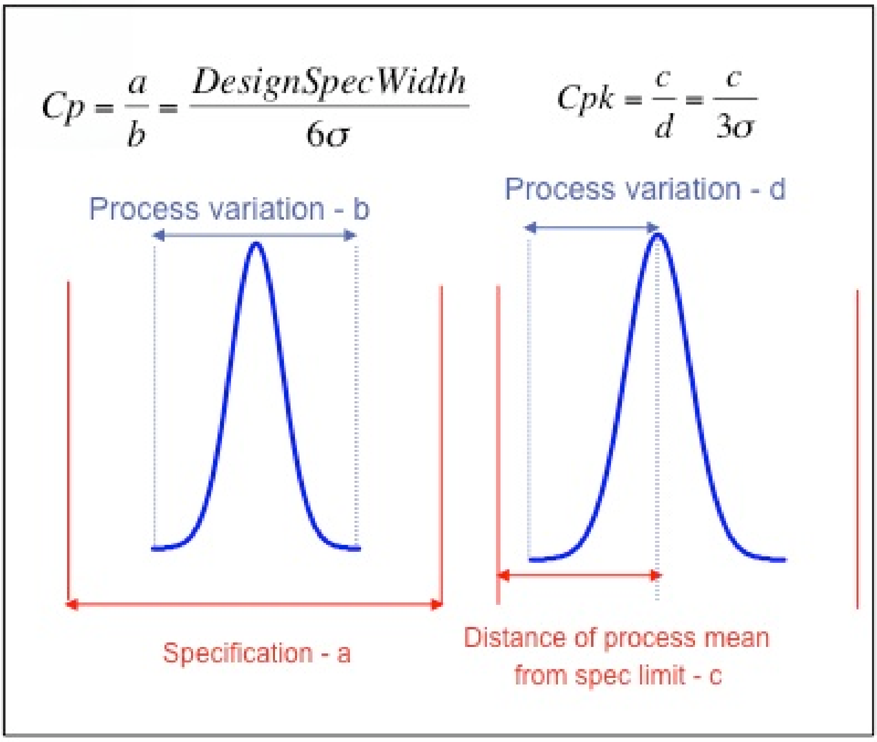

Figure 2.5: *A definition of the Cp and Cpk capability indices. Adapted from isixsigma.com (2008)*

Manufacturing and process capabilities are typically manifested through the assigning of tolerances to all manufacturable design parameters. These parameters will always display some degree of statistical variability due to common cause variation in factors such as material quality, machining stability and environmental conditions. A tolerance is the permissible range that the quantity may vary from that specified without detrimentally impacting functionality or performance. Swift et al. (1999) state "there is probably no other design improvement effort that can yield greater benefits for less cost than the careful analysis and assignment of tolerances."

Tolerance allocation is of significant importance for the functionality of mechanical products and the manufacturing cost of the parts. Gao and Huang (2003) define the two principal tolerance groups required for optimal tolerance design; these are product tolerances, which address the functional requirements of the product, and process tolerances, which address the production procedures and tooling requirements undertaken to manufacture that specific feature. According to Nickolaisen (1999), design tolerance allocation has traditionally used a combination of trial-and-error, design carryover and tacit process expert opinions to assign product tolerances. Day et al. (2005) identify the need for a data-driven system to assign process capable tolerances by defining mathematical functions for all factors of variation.

2.7 Key Characteristics and Critical Features

Thornton (1999) raises the issue that, in the design of a complex product such as the aircraft engines considered in this study, it is simply not possible to control and monitor all features specified on a product drawing. Organisations thus often define critical features, or ‘Key Characteristics’ (KCs), to identify where variation has the most significant affect on product quality and performance. This aids in highlighting the features and tolerances that warrant priority attention from manufacturers.

In order to quantify and justify the selection of KCs, Thornton introduces the concept of a ‘Key Characteristic Flowdown’, which provides a systemic view of potential variation risk factors via a hierarchical picture of those product requirements that are most sensitive to variation as a function of the part and process features variations that define them, as displayed in Figure 2.6:

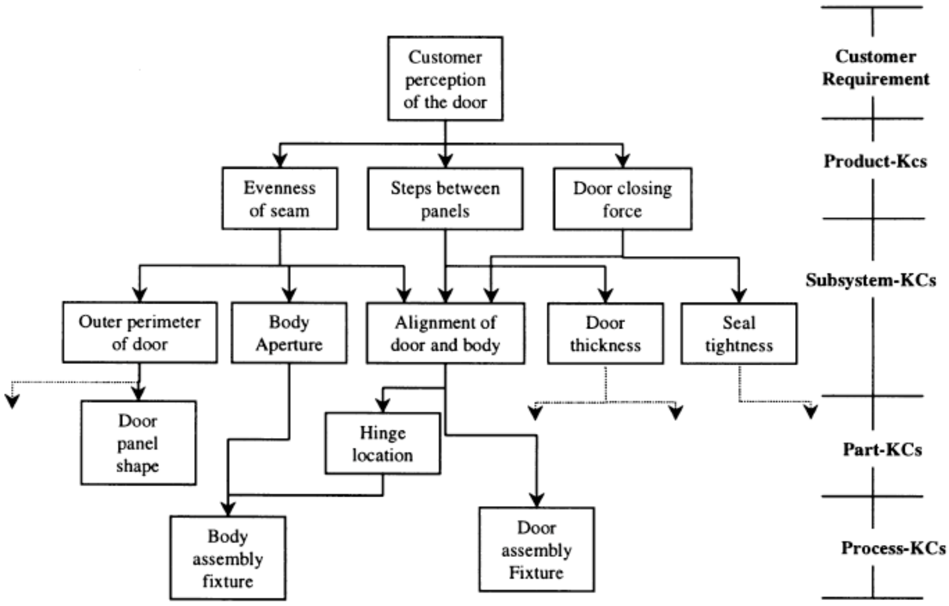

***Figure 2.6**: A Key Characteristic Flowdown. Adopted from Thornton (1999)*

Such a roadmap assists in analysing the interaction between key characteristics, identifying where process changes will directly impact product quality. Thornton emphasises the need for on-going monitoring in order to detect the effects of process degradation caused by factors such as tool wear, operator and supplier change before the final product is compromised.

2.7.1 Database Architecture and Modelling Methodologies

This chapter has so far introduced the subject areas of DfMA and process capability analysis and their relevance in promoting effective concurrent engineering practice. This subject matter culminates in the selection and formalisation of databases and modeling representation to facilitate the information management highlighted in the theory explored. The rest of the chapter looks at a small sample of case studies presented in the literature, highlighting some of the benefits and knowledge attainable by optimal data exploitation.

Barton et al. (1996) describe a database architecture and a statistical modeling methodology that enables the formal capture of manufacturing experience as new or revised design rules within the contextual example of printed circuit board assembly (PCA).

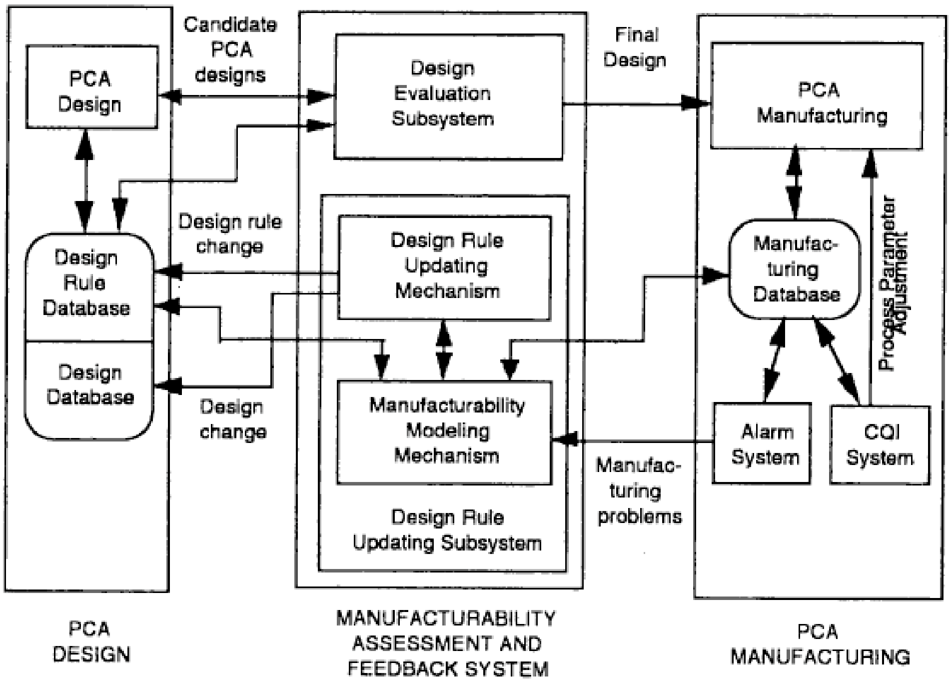

Figure 2.7*: System structure (decomposed model). Adopted from Barton et al. (1996)*

The architecture proposed in Figure 2.7 consists of two principle databases- the design rule database and the manufacturing database (which includes key test data and process parameters in storing capability limits and problem characteristics). A manufacturability modeling mechanism then captures the quantitative relationships between manufacturability measures (dependent variables) and associated product and process design parameters (independent variables). Such a system encourages the automatic updating of design rules based on manufacturing capabilities.

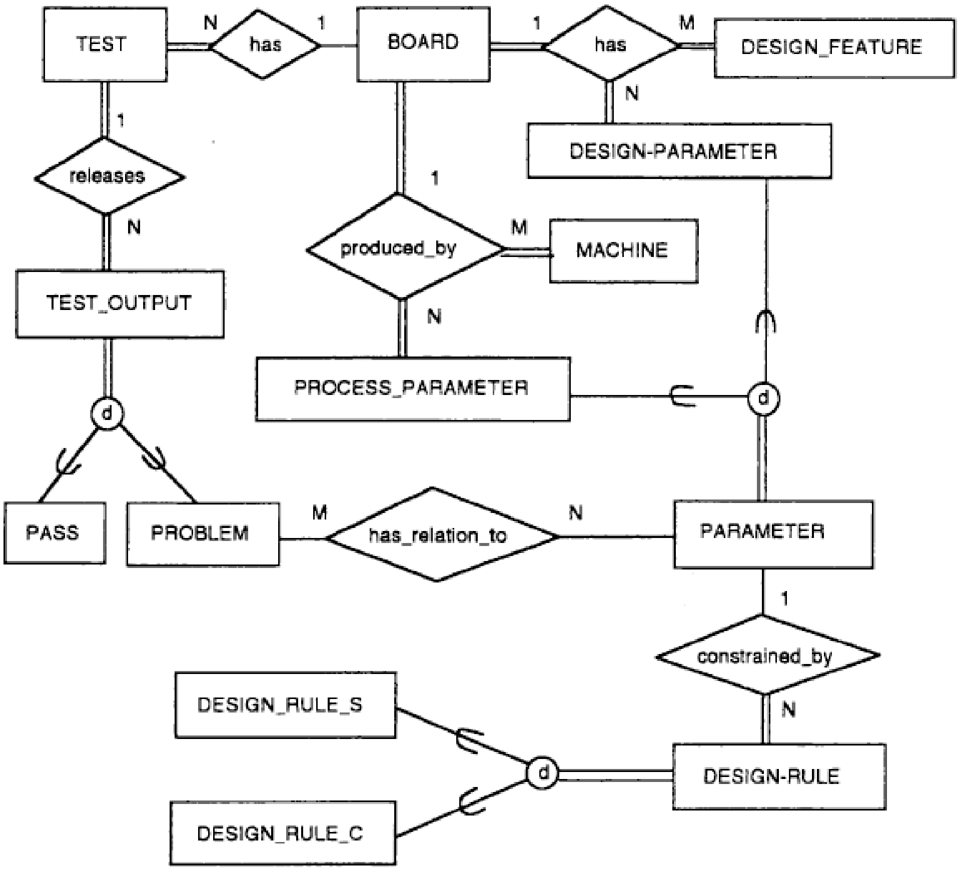

Figure 2.8*: The proposed information model- EER diagram. Adopted from Barton et al. (1996)*

Figure 2.8 uses Enhanced Entity Relationship (EER) modeling to depict relationships and interdependencies between various design and manufacturing parameters within a process capability database. This helps designers take a holistic view of product performance and understand interactions between components.

A Process Capability Database (PCD) typically houses historical process capability and performance data, containing technical attributes including feature details (dimensional and descriptive), material properties and process details in addition to nominal and target tolerances. PCDs are primarily used during product design to allocate tolerances or forecast and manage manufacturing variation. Delaney and Phelan (2008) note that using a PCD for these purposes alone does not exploit its full potential. They propose a model for predicting product performance variation from early design using the information contained within such a database.

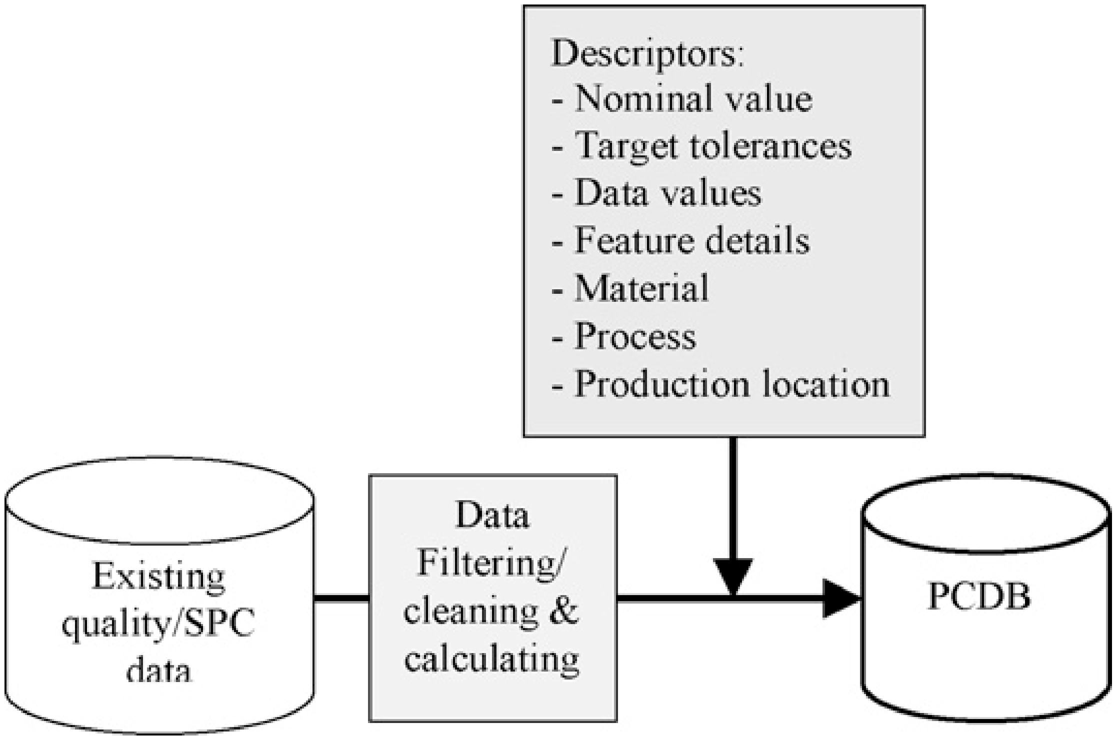

Figure 2.9:*Outlining a process to create the Process Capability Database. Adopted from Delaney and Phelan (2008)*

Figure 2.9 demonstrates the requirements of data mining and metadata descriptors in withdrawing optimal process capability information from existing SPC data. The authors propose a database whereby not only is all descriptive information concerning features and attributes held in an accessible format, but also where the percentage contribution of each input to defining a parametric variance is calculated automatically. The figures are calculated using the variance equation put forth by Morrison (1957). Take a generalised mathematical formula in the form:

$$X = f(x_1, x_2, x_3, \ldots, x_n)$$

Where X is the target for some property of the product and x_1, x_2, x_3, etc., are parameters entered in the design formula. The variance *V(*X) is the statistical measure of variability, and is defined such that:

$$V(X) \approx \left(\frac{\partial X}{\partial x_1}\right)^2 V(x_1) + \left(\frac{\partial X}{\partial x_2}\right)^2 V(x_2) + \left(\frac{\partial X}{\partial x_3}\right)^2 V(x_3) + \cdots + \left(\frac{\partial X}{\partial x_n}\right)^2 V(x_n)$$

The formula is exact for linear functions and is a good approximation for non-linear functions if the standard deviation of each variable is less than 20% of the mean.

	Nominal	Sigma	Variance contribution (%)
Width (mm)	0.35	0.005	3.056
Thickness (mm)	0.2	0.001	3.369
Length (mm)	6	0.05	9.358
E	110000	(Const)	-
Deflection (mm)	2	0.15	84.218
Results:			
Force (N)=	***0.713***		
Sigma (F)	***0.058***		

Figure 2.10: *User interface created by the authors to allow engineers predict the variation in normal force based on variation of the inputs. Users input data into the boxes shaded in grey. Adopted from Delaney and Phelan (2008)*

The variance contribution is presented to engineers so that they will understand the dominant contributors to the overall variation. In Figure 2.10, where the variance equation has been applied to the example case study of the construction of an electrical connector, it can be seen that the input factor 'deflection' variance accounts for more than 84% of the total variance for the 'force' parameter, thus warranting priority attention.

This is one example from the expanding field of probabilistic design. As identified by Swift et al. (2001), there are a number of mathematical methods for predicting process capability indices for given design geometries, materials and processing routes. Although parametric variation can never be fully eradicated, it can be minimised and controlled through early and quantified knowledge of all sources of variation.

2.8 Evaluation and Research Gap Analysis

Since Boothroyd and Dewhurst proposed DfMA methodologies in the early 1980's, a wealth of further study and investigation has been dedicated to the field. This chapter looked at different considerations, frameworks and procedures required to implement such methodologies within a large cross-section of manufacturing environments. This aids in streamlining product lifecycle development, creating a better product and service to the customer. Similarly, a wide range of methods of statistical process controls and tools have also been subject to much research and development throughout academia and manufacturing industries in recent years, in line with both improved measurement technologies and analysis software and the drive towards Lean and controlled production for higher quality products.

However, the two aforementioned concepts remain largely uncoupled throughout the current literature and case studies. Some primary knowledge gaps have been identified:

- There lacks an inter-relation between the establishment and promotion of a new DfMA framework and the significance of quantified process capability analysis;
- There lacks a clear definition of what manufacturing and assembly knowledge is required throughout each stage of concept and component design within the aerospace industry;
- It is not established how such capability transfers can be formalised as standard within the design and buy-off process.

This research aims to address these knowledge gaps by building a framework to formalise the integration of capability knowledge and data into a structured product design and development process.

2.9 Summary

This chapter has identified the key considerations required to establish a successful concurrent engineering environment from which to develop a DfMA framework based on current manufacturing capability:

- The need for 'Matrix management' and cross-functional product teams;
- The realisation that up to 80% of costs are defined during early concept design;
- The incorporation of evolving CAD/CAM systems and automation;
- The promotion of feature-based thinking and design rules;
- The need for a formal Knowledge Management dimension;
- The role of process capability analysis and Statistical Process Control (SPC);
- The definition of key characteristics and critical features.

To conclude, the principle findings relevant to the project were evaluated and a number of knowledge gaps are identified. Based on the established project scope, objectives and literature analysis, the proceeding chapter describes the methodology followed in realising the research aims.

3 METHODOLOGY

3.1 Introduction

There are a number of different research methodologies available to use when conducting research. It is important to define and adopt the most appropriate method in order to best exploit the information and resources available to the study at hand. This chapter describes the selection between quantitative and qualitative research methods and inductive and deductive reasoning to define the project methodology. The chosen methodology describes four primary stages of progression required to build and validate the solution framework.

3.2 Quantitative and Qualitative Research Methods

Research methods can be broadly categorised into two principle types: Quantitative and Qualitative methods. Quantitative research methods, as defined by Weinreich (1996), are designed to ensure objectivity, generalisability and reliability. Such methods are used when the reality is objective and singular and the researcher knows exactly what information is being sought. Quantitative methods concentrate on what can be measured and organised into statistics, following a deductive method of research whereby the key purpose is to collect evidence to substantiate or disprove existing ideas and theories.

The contrasting method of qualitative research involves more subjective and opinion driven data, and is usually word based and value laden. Qualitative research follows an inductive approach where specific observations and measurements are tested and built up to derive a theory or conclusion. This research task follows an inductive approach, whereby a process framework is established and built up based on an investigation of practice and an assessment of company requirements. As a result, a qualitative methodology was adopted, using the primary tools of semi-structured interviewing and subjective observations to collect and analyse information from which to draw conclusions and build a solution.

3.3 Research Methodology

Figure 3.1 displays the structure of the research methodology selected for this research project, consisting of four primary stages:

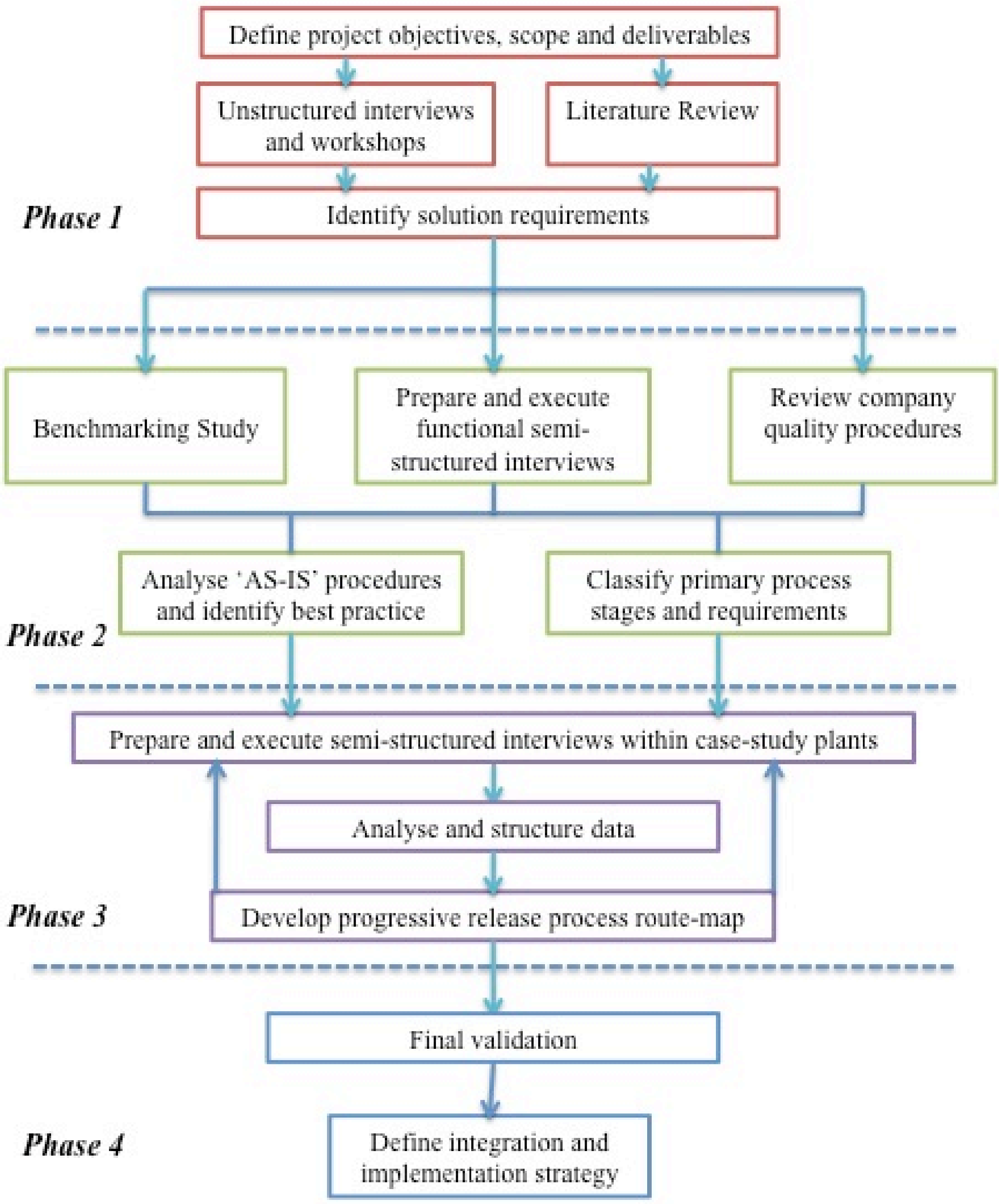

Figure 3.1: *Research Methodology*

3.3.1 Phase 1- Project Initiation and Scoping

Phase 1 of the research term was dedicated to gaining an introduction to the company structure of operation and the nature of the problem itself within the wider context of product introduction. A series of ten unstructured, hour-long interviews with design and manufacturing functional representatives were carried out to discuss the problem posed by the company in relation to current practice and identify the requirements from the solution. A number of product introduction workshops were attended in order to gauge the role of the project within product development and lifecycle management.

A comprehensive literature review was undertaken to place this research in context of the wider research field and identify key considerations when creating a DfMA framework. The keywords of 'Design for Manufacture', 'Design for Assembly' and 'Process Capability' were used to search across the Cranfield University library and interactive journal subscription catalogue and locate initial reading sources from books, journals and websites. From the initial analysis of returned abstracts, the most appropriate sources and journals were identified for wider investigation and citation searches. Once the relevant literature set had been sourced, all pertinent information was profiled and analysed to identify the key findings and match their use and significance to the project in hand. In total, over 60 sources were consulted, both for direct references and for general topic reading.

3.3.2 Phase 2- Information Gathering

A number of methods were followed in order to capture a valid, non-biased and broad data and information set from which to build the knowledge solution and framework. The purpose of the information gathering stage was to profile the current practice of progressive model definition and identify the key requirements of the solution framework. This was accomplished by following three primary information streams that ran largely concurrently as research progressed.

- **Company interviews and workshops**

  To assess current practice within the sponsoring company, a series of twenty hour-long interviews and workshops with a total of thirty employees were undertaken. Participating interviewees included representatives from central design, assembly and manufacturing functions in addition to teams from specific component manufacturing plants. The purpose of the semi-structured questions was largely to examine and scrutinise examples of previous model releases, which aided in achieving a better step-by-step visualisation of the company method of practice and identifying inefficiencies and flaws experienced from this. All information was collated and analysed with respect to defining the key activities and skeleton structure of the solution framework based around optimal practice and the opinions of the employees.

- **Benchmarking investigation**

  To understand different practices of design and product development across companies producing products of a similar nature and complexity, a modest benchmarking investigation was undertaken within the automotive and aerospace sectors. This was carried out through eight direct, semi-structured interviews resulting from two company visitations- one to a leading aircraft manufacture and one to a process capability analysis consultancy working with aerospace and automotive clients.

  Interviews were designed based on the key findings of the literature review and were centered around gauging manufacturing and assembly involvement in progressive model design, exploring and questioning the success of different practices adopted. In addition, through exploiting links within the company and through Cranfield University, combined with an extension of the literature review to specific company publications and case-studies, information from four other automotive manufacturers and two aerospace companies was also incorporated for a wider comparison.

- **Review company operating and quality procedures**

  On a more technical level, it was important to analyse all internal company procedures, standards and resources that contribute to progressive model releases and product definition. The purpose of this was to ensure that the framework complemented existing procedure and integrated directly into the company structure through direct linkage and referencing to supporting material.

3.3.3 Phase 3-Solution Development

After classifying the primary process stages, the progressive release route-map was constructed and populated with information through the further use of ten hour-long interviews and workshops. These were carried out through three contrasting case-study component plants chosen in order to collect an unbiased and broad company information set. Questions posed to integrated product introduction team members were based directly around the process activities in order to identify the participants and the inputs and outputs at each stage.

Information was analysed and categorised for each activity, whereby the framework evolved through the population of each point into a structure process route-map. IDEF0 modeling was used to better visualise the process before adaption to the company-defined format. Feedback loops were utilised as the solution developed in order to tailor interview questions to the evolving framework.

3.3.4 Phase 4- Validation and Implementation

Phase 4 details the methods followed to achieve final validation of the framework and implement it within company practice. Validation was achieved via a series of structured interviews with experts based directly on the process route-map, where the information within each activity was analysed to ensure agreement and completeness.

Following completion, the route-map was made live and integrated into the company intranet before being trialled within a series of drawing and design buy-off sessions.

3.4 Summary

This chapter has described the adopted qualitative research methodology and categorised the four principle stages defined in order to achieve the project objectives. The primary methods and tools of collecting and analysing information are introduced as a series of internal semi-structured interviews, a comparative benchmarking analysis and specific contextual case-study foci. The next chapter further describes the information gathering activities undertaken and profiles the principle findings resulting from an assessment of current practice of progressive model definition within the sponsoring company and across the aerospace and automotive sectors.

4 CURRENT PRACTICE OF PROGRESSIVE MODEL DEFINITION

4.1 Introduction

In order to develop a current capability design for manufacture framework, it was first necessary to analyse the current practice and procedures followed within progressive model definition and release. The purpose of this was to gain a better comprehension of all the considerations and factors that influence and define the process and to identify shortcomings in existing methods.

This chapter details the methods of information gathering taken to analyse the current practice within the sponsoring company and across the aerospace and automotive sectors. The primary method of information capture adopted was an extensive series of interviews and workshops with contacts involved in product design and development from across business functions. This process was accompanied by an in-depth analysis of existing company procedures and a benchmarking investigation to assess the effectiveness of practice followed within other organisations.

4.2 Information Capture

4.2.1 Interviews and workshops

Figure 4.1 displays the job roles of the thirty individuals who participated directly in the research project. The majority of the individuals held senior roles within their division, and the average years of experience within their specialist sectors ranged from 7-30 years. In order to accurately represent all functions involved with progressive model definition and release, individuals from central assembly, design, material science and operations were included in addition to those involved from the five component manufacturing plants that were visited at different locations throughout the UK.

Function	Employees
Strategic Operations	Product Introduction Manager Manufacturing Engineering Excellence Executive Process Excellence Manager Chief of Product Introduction Chief of Strategy- Manufacturing Engineering Purchasing Manufacturing Engineer Process Excellence Leader Specialist Knowledge Management
Central Design	Cost Modeling Team Leader Chief Design Engineer Process Development Manager Process Excellence Champion Design Process Improvement Engineer
Case-study component plant- Turbine Blade Facility	Product Introduction Team Leader Standard Features Research Analyst Advanced Definition Engineer Manufacturing Engineer
Compressor Facility	Chief of Product Introduction Transition Manager Manufacturing Engineering Team Co-coordinator Principle Manufacturing Engineer
Case-study component plant- Front-body Housing	Head of Product Introduction Integrated Team Leader Advanced Manufacturing Engineer
Case-study component plant- Rotatives	NPI Team Leader Leadership Graduate
Central Assembly	Project Technical Leader Business Development Manager
Combustion Plant	Manufacturing Engineer (x4)
Material Science	Materials Application Team Leader

Table 4.1: *Company interviewees*

There were three primary stages of interviews held throughout the duration of the project, with each interview personalised to the interviewee in question. During the project initiation phase, the author undertook hour-long unstructured, informal interviews and discussions with the ten primary contacts participating in the research project. This included functional representatives from central design and manufacturing engineering in addition to integrated product team members who work on the production of a specific component. The purpose of these interviews was to discuss the main project aim and better comprehend the problem posed through gaining an initial understanding of the top-level company approach to product design and development.

In order to capture current practice and identify the requirements from the solution framework, semi-structured interviews, each lasting approximately an hour, were undertaken created to gauge that individual's role and requirements from the progressive model release process. Appendix I shows an example questionnaire posed to a Manufacturing Engineer working within one of the specialist component plants. The interviews were structured around investigating the following questions:

- What are the key stages and milestones of design release?
- What individuals and functions are involved at each stage?
- What methods and media of communication are adopted?
- How are manufacturing capabilities communicated and used?
- How are lessons learnt captured and used?
- What are the major causes of setbacks or delays within current practice?
- What resource management and production planning tasks are directly coupled to the design buy-off?

The questionnaires helped gauge the key considerations and inefficiencies with current practice. When analysing the results from the questionnaires, it was important to distinguish between case-specific and generic points to carry forward for implementation into the framework. Bias was eliminated through the high number and variety of contacts interviewed.

- **Analysis of company procedures**

The research student spent the majority of the research term working within the company itself, having full access to the IT infrastructure and intranet where there can be found a number of internal resources intended to facilitate, standardise and implement the larger product development process. The 'Rolls-Royce Quality Management System', or RRQMS, is a large network containing a series of detailed 'Global Quality Procedures', or GQPs, which each set out specific procedures, metrics and audits to facilitate and ensure that quality is driven into every company output.

An analysis of these procedures was deemed necessary for the more technical integration of the framework within the company. It was important to locate and incorporate procedures for drawing standards, communication formats and PLM data input into the framework itself, as these are key requirements to adhere to throughout a model definition and release. In addition, for completeness and increased utility, links to sequential and related processes including manufacturing resource planning and quality and inspection analysis were sourced for direct inclusion.

4.2.2 Benchmarking study

In order to add breadth to the study and to examine alternate practices followed within the wider industry producing products of a similar complexity and volume, a small comparative benchmarking study was undertaken involving a number of aerospace and automotive manufacturers. Hour-long interviews were based around gauging manufacturing and assembly involvement in progressive model design and questioned the success of different practices adopted. The job titles of the eight individuals interviewed were:

- Quality assurer, Digital Integration (2)
- Head of Manufacturing Engineering Information Systems
- Manufacturing Engineering Support Engineer (3)
- Predictive Capability Software Developer (2)

Appendix II shows the generic semi-structured questionnaire used within the benchmarking interview sessions. This was adapted and personalised dependant on the company and individual under interview, but largely took a constant format, beginning with some general questions concerning the subject's job responsibilities and role within product realisation. Following on, more specific questions were then asked concerning practices followed within that company, taking a similar format to the internal questionnaire with the questions posed. These questions were categorised into three main sections: 'Progressive design release', 'Capturing manufacturing capabilities' and 'Statistical process analysis'.

In addition, through exploiting links within the company and through Cranfield University, combined with an extension of the literature review to specific company publications and case-studies, information from four other automotive manufacturers and two aerospace companies was also incorporated for a wider comparison. This included four further discussions with Rolls-Royce employees concerning their past employment experiences within other automotive and aerospace companies. The benchmarking assessment carried out highlighted the unique approach adopted by each company, allowing an assessment of alternate practice methods for consideration in constructing the solution framework.

4.3 Current Practice

During the project initiation phase, it quickly became apparent that there was minimal process definition or standardisation of the progressive release process employed within the company. Figure 4.1 shows the basic, top-level recommended process employed by the company, with feedback loops indicated to allow iteration and the revisiting of points before the model is completely agreed by the manufacturing function.

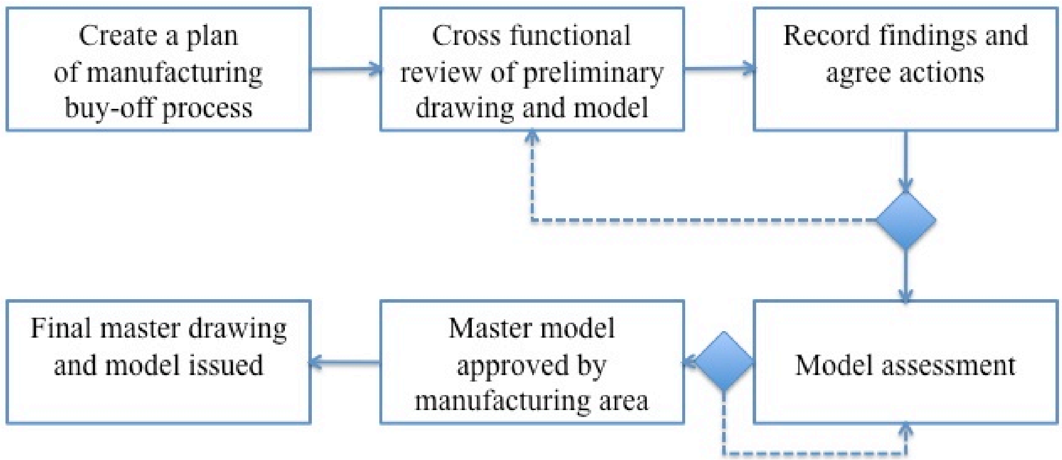

Figure 4.1: *The existing approach to progressive definition release and buy-off*

The existing process lacked the depth of information necessary to organise and structure the period of model release and buy-off. There was no further detail governing, for example, what considerations need to be incorporated when creating the buy-off plan, or how a cross-functional review should be approached. As a result, each instance was approached in an ad-hoc manner and varied greatly across component plants and projects. Although a degree of variation and process adaption within each case is required due to the different component and method of manufacture employed, problems arose mainly due to the lack of tailored, planned buy-off around manufacturing lead times, or through non-adherence to concurrent definition procedures and communication standards.

In addition, the process does not include a specified feed-in of available manufacturing capability knowledge before main buy-off. The benchmarking investigation highlighted the successful utilisation of specific data and information feed-in points throughout product development within other companies, aiding a more informed design process. Such a concept was not present on a wide or formal scale throughout the current company practice, which resulted in design being largely unaware of quantified production capabilities. This raises problems and adds additional complexity to buy-off discussions once the model is released.

The main problem areas identified with current practice were summarised (Table 4.2) alongside the resolving solution, which was identified and assessed during interviews and using the key findings of optimal DfMA identified within the literature review:

Subject	**Problem**	**Solution**
Capturing lessons learnt	There is no formal or uniform method for capturing and using tacit knowledge	Extract lessons learnt through the promotion of regular plant reviews and categorise knowledge by feature or part
Integrated product teams	The integrated product team often lacks key representation, leading to problems in realising design	Actively assess the required representation before commencing on a progressive release and define required signatories at each stage of definition
Reliance on predecessor models	There is high tolerance carry-over from previous designs that is unassessed or unconfirmed	Mandate a system of inclusive positive confirmation for all assigned tolerances
Data and procedural standards	There are frequent discrepancies and errors adhering to changing data management procedures caused by the move towards PLM.	Specify and link to present data standards, inputting procedures and related documentation
Communication methods	There are frequent discrepancies and errors in adhering to correct communication and sign-off rules	Specify and link to communication templates and standards. Ensure all required agreement signatories are in place before the model is released
Model standards	There are frequent discrepancies and errors in adhering to correct model and nomenclature standards	Specify and link to model standards and checklists
Early manufacturing awareness	Delays are created when manufacturing are largely unaware of the impending product	Promote early manufacturing involvement and component family knowledge to commence production planning
Conformance checklists	Problems arise where a model is released without ensuring comprehensive adherence and completeness	Place gate checklists following each primary activity in the release process to ensure that all tasks within that activity have been completed in full
Project milestones	The release project is often ill-defined and unorganised with respect to the wider project	Plan the progressive release to correspond to all larger project milestones and reliant activities
Critical features	There is rarely any justification by design on designated critical features	Ensure design presents and explains designation and role of critical features before buy-off commences

Table 4.2: *The problem-solution matrix*

4.4 Summary

This chapter has detailed the methods of information gathering and analysis followed in order to profile the existing procedure of model definition within the company. This was primarily achieved through a series of internal semi-structured interviews that aided in identifying the key shortcomings of current practice and the optimal format for the solution framework. In addition, a benchmarking assessment aided in identifying alternate practice followed within the aerospace and automotive sectors. The next chapter discusses the formulation and development of the progressive release process route-map.

5 DEVELOPMENT OF A PROGRESSIVE DEFINITION FRAMEWORK

5.1 Introduction

In order to promote optimal concurrent engineering practice and knowledge management throughout the definition of a design model, it is vital to organise and structure the model release process in a way that facilitates effective communication between the product introduction functions. This chapter describes the progressive definition release route-map produced in order to eliminate the flaws identified with current practices and produce an optimised and uniform process. The route-map is dissected step-by-step with an expansion on the principle activities of the process before the chapter is concluded with a brief summary.

5.2 The Framework

The formulated framework took the form of an interactive process route-map as part of the Rolls-Royce Production System (RRPS) 'How to' guides. The RRPS is a best practice framework for improving and maintaining business performance. The RRPS intranet page houses a series of guidelines and process maps which guide employees to implement standardised and developed procedures of best practice. These maps guide the user through analysis and implementation of a variety of different tasks, ranging from production planning and control to supply-chain and quality management. The standard format consists of a hypertext-enabled PowerPoint® flow chart, where clicking on each stage takes the user through to sequential layers of information and links to associated documentation.

Such practices assist in minimising waste and variation, streamlining and simplifying methods of operation whilst still permitting innovative and improvement ideas of employees to be incorporated. The system is centred on people, and utilises the two main strategies of Lean and Six Sigma to enable optimum process maturity through a four stage improvement journey: Defining the process basics, gaining process control and standardisation, improving process flow and finally by improving process capability.

5.2.1 Top-level Route Map

When the route-map is selected, the user will be directed to the top-level route map, as displayed in Figure 5.1. The process is broken down into key activities (blue circles), checklists for progression to the next stage (yellow boxes) and related documentation and links (red ovals).

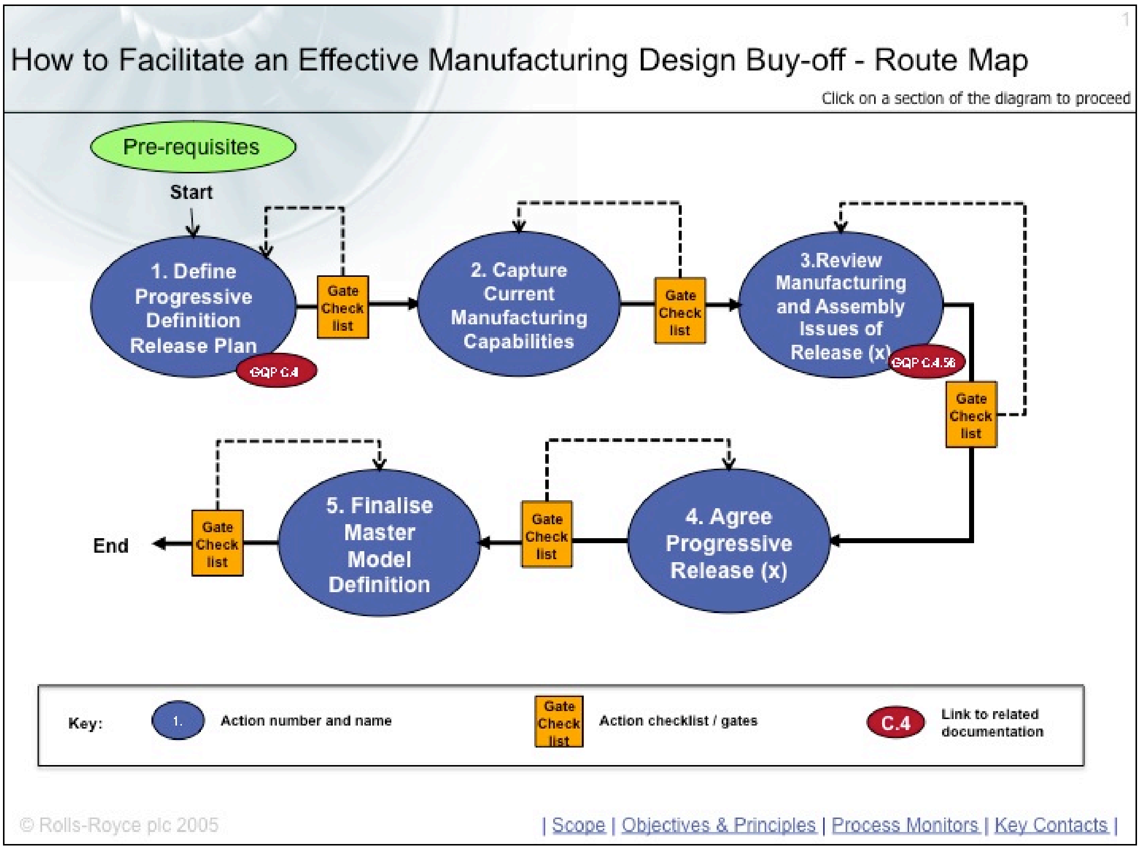

Figure 5.1: *The Progressive Definition Release Route-Map*

Also included on the top-level view are links to the scope, objectives and principles of that map. These pages describe to users the key purpose of the route-map, guidance on applicability and an introduction to the theory and principles behind it. Figure 5.2 displays some example screen-shots from the 'Objectives and Principles' section, stating the purpose of the route-map alongside a summary of the expected benefits to arise from its use. The process is also placed in context of the wider company product introduction landscape.

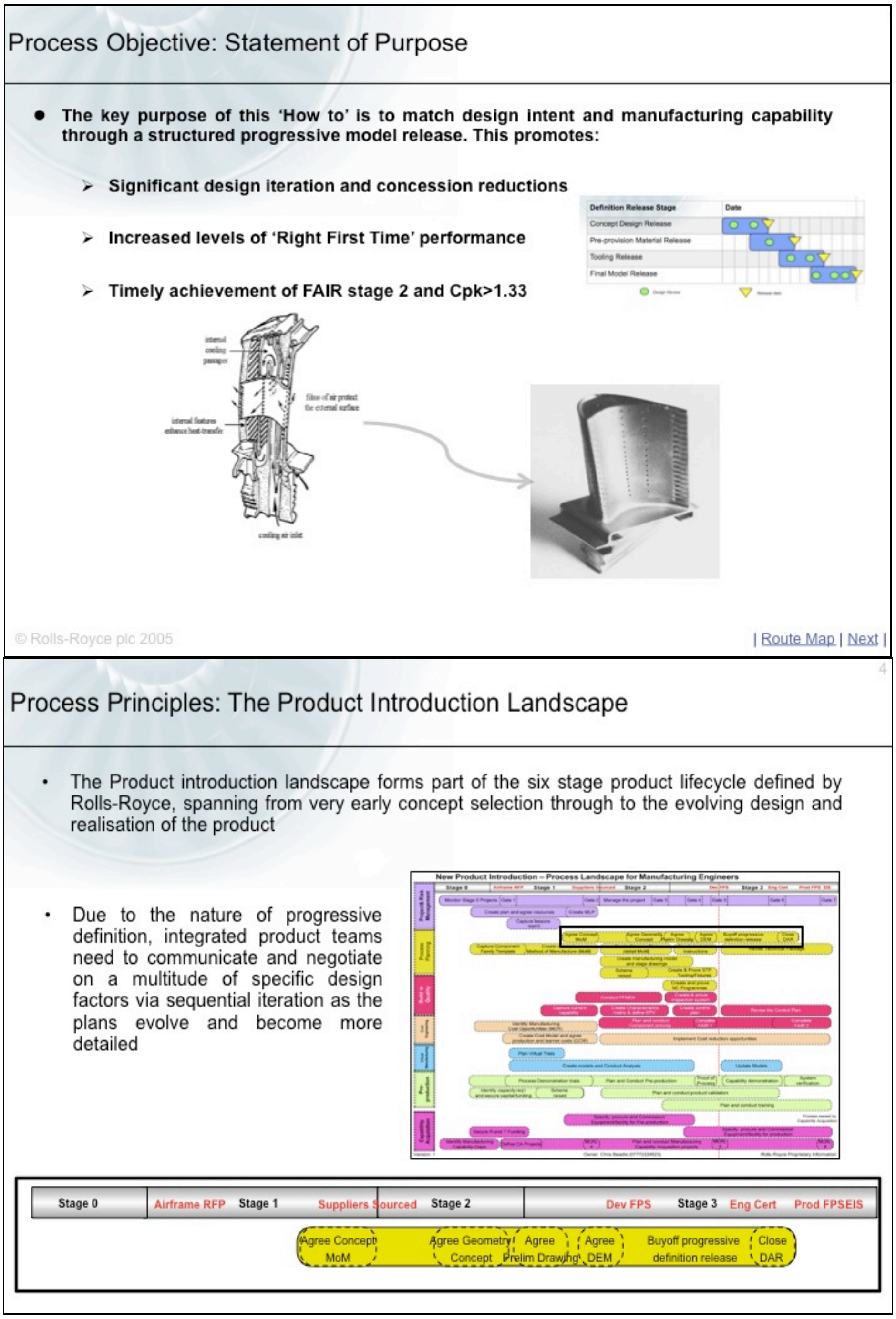

Figure 5.2: Process Objectives and Context

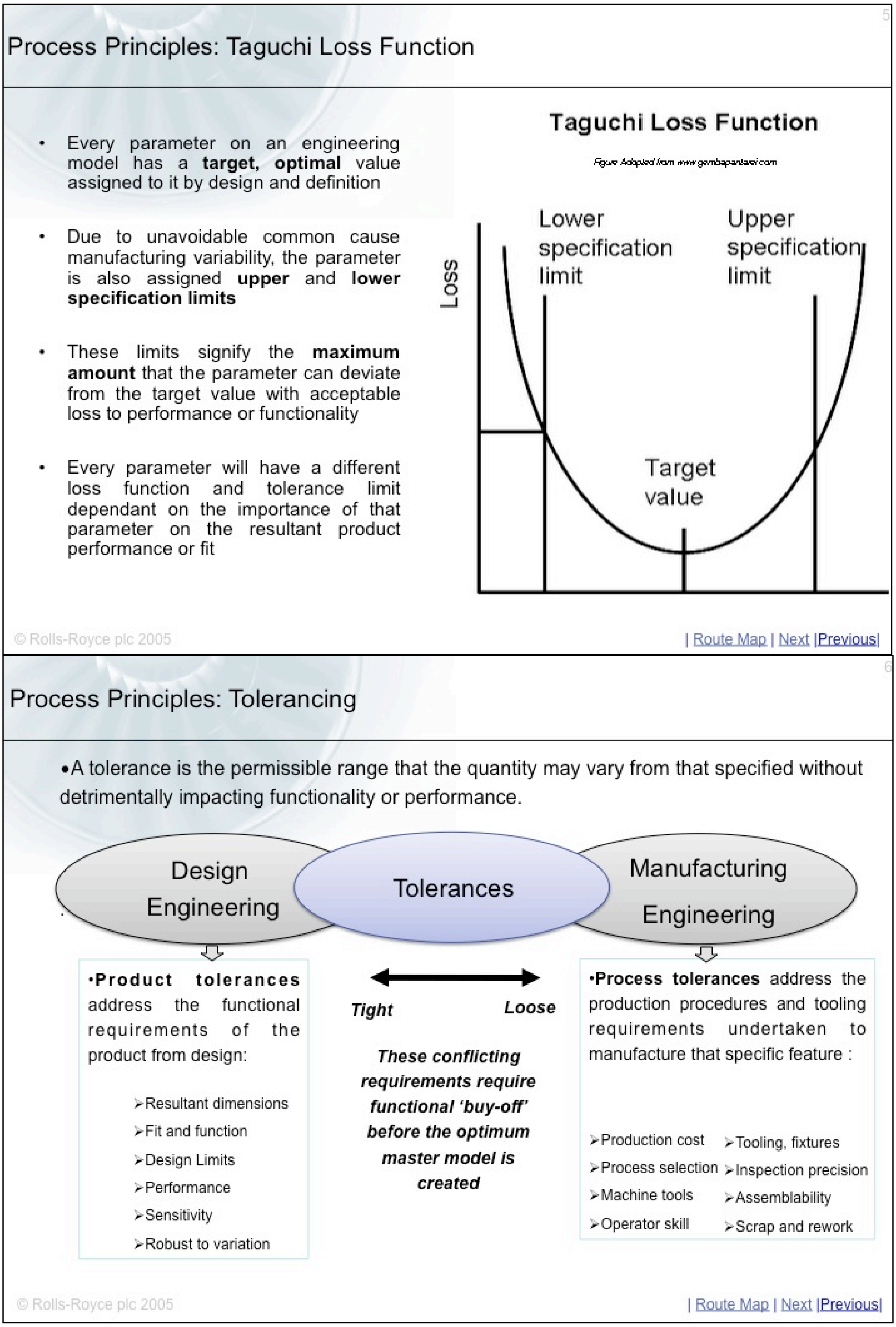

Figure 5.3: *Process Principles and Theory*

Figure 5.3 displays some example screen shots detailing the theory section of the process introduction. The Taguchi loss function (Gemba Panta Rai, 2008) is used as an illustration of the importance of intelligent tolerance allocation. Tolerances are identified as the primary manifestation of buy-off, and the differences between product and process tolerances are highlighted.

This chapter continues by analysing the content behind each of the five main activities in the route-map. Each activity consists of a series of interactive steps that are broken down into further levels of information. At the end of each activity, a 'Gate Checklist' poses a series of questions to the user to ensure that all requirements specified in completing that activity have been met before progression to the next stage.

5.2.2 Activity 1- Define Progressive Definition Release Plan

This activity addresses the foundations required from which to carry out an efficient model release process. It supports the establishment of an integrated product team to create a plan for the progressive release of a model, defining stages of release based on manufacturing scheduling requirements. The activity is divided into three primary stages: (1) Establish the team, (2) Define the progressive definition release plan and (3) Establish the design and communication media.

1. **Establish the team**

   An important pre-requisite to a progressive definition release is the formation of the team of individuals and functional representatives that shall take part in facilitating that release. It is vital to ensure that all necessary representation is in place from across product introduction functions to promote an informed and realisable design. This must include the central design, manufacturing and assembly functions involved with buy-off.

   In addition, specialist disciplines such as cost engineering, resource planning or material science are required at specific points in model release to analyse and substantiate specific design scenarios. When selecting the integrated team, it is also vital to include any necessary representatives working on interfacing components or units that may be affected by the model definition plan.

2. Define progressive definition release plan

Once the product team is established a plan and schedule for the progressive release can be formulated, defining levels of release in order to deliver parts just in time for build within the larger product introduction timescales. Each release should be defined via the following parameters as a minimum:

- **Level of definition maturity;**
  Detail of what features and requirements are to be specified in the model

- **Date of design review meetings;**
  Scheduled with respect to release date in accordance with manufacturing planning

- **Release date;**

- **Required functional signatories for release.**

By adhering to such planning, the team define in advance what features require priority definition due to material or tooling lead times. Specifying the required agreement signatories at each stage ensures that positive acceptance is gained from all necessary functions to adhere to the design. Any non-agreement or problems are highlighted immediately before any further design work commences.

3. Establish design and communication media

The nature of model release and buy-off within an extended team means that a lot of documentation will be communicated within the team throughout the release period. The purpose of this stage is to establish standards and folders to regulate and organise all edited models, notes and calculations that pass between members in accomplishing buy-off. This point also links to company drawing standardisation and acceptance procedures.

5.2.3 Activity 2-Capture Current Manufacturing Capabilities

Due to the high-level of design and feature carryover for new products, an extensive awareness of manufacturing capability can be established before the model is first released. Activity 2 describes how to create an enumerate capability forecast for each feature or requirement on a model through a translation of qualitative knowledge and capability performance data. This process provides the team with quantified manufacturing capability to realise the design, enabling a more informed and data-driven buy-off for each specific feature. Quantitative capability data is based around the nominal value and tolerance bands assigned for each parameter on a feature. The activity is divided into four primary stages: (1) Identify component family, (2) Capture current manufacturing capability, (3) Forecast future manufacturing capability and (4) Prepare a capability forecast.

1. **Identify component family**

   The first step in assessing manufacturing capability to produce a product is to identify the family or group of components that the new product belongs to. Components are frequently grouped together based on similarity or relation of features, promoting not only standardisation and organisation of parts but also data and information reuse across parts where appropriate.

   Such grouping is particularly prevalent within the aerospace industry, where new products contain a vast amount of design carry-over and similarities with previous products. By identifying the component family, top-level methods of manufacture, specifications and operation listings can be identified in the first step of planning production and analysing capability.

2. **Capture current manufacturing capability**

Specific feature and requirement capability can be analysed using local databases of measurement information and Statistical Process Control (SPC) data on current and previous production parts. The type and amount of such data will vary widely dependant on the product, plant and measurement systems in place.

Key Performance Indicators (KPIs) can draw out quantitative capability measures from this data. Some common KPIs used in analysis include:

- Performance Capability Indices (Cp and Cpk)
- Right-First-Time (RFT) levels
- Non-conformance (Parts Per Million)

Assessing the achieved capability of each feature and requirement allows the discovery of any corresponding inefficiencies and improvements identified during manufacture. In addition, holding manufacturing plant ‘lessons learnt’ reviews at the closure or commencement of a project assists operators and manufacturing engineers in exposing and categorising best manufacturing practice. By mapping the manufacturing process into key stages, general production best practices at each stage of manufacture can be identified.

3. **Forecast future manufacturing capability**

Future as well as current manufacturing capabilities must be taken into account during buy-off. This is especially relevant for new or changed manufacturing methods where current capability knowledge is sparse, as the introduction of any new machinery, processes or materials will undoubtedly have an effect on the resultant capability.

Such forecasting is achieved through:

- Analysing the output from trials of new processes or machines;
- Extrapolating long-term SPC trends;
- Undertaking process modelling to analyse relationships and interdependencies between variables

4. Prepare and issue capability report

All capability data and information collected should be placed into a standardised template detailing the predicted capability for each feature and requirement parameter on the drawing. This report is circulated to all members of the core team before official buy-off begins, and gives the design function an explicit indication of manufacturing capability.

Identification		Previous capability						Parameter manufacturing limits		Cpk = 1.33		Additional comments
Reference	*Feature/ Requirement description*	*Target value*	*USL*	*LSL*	*Cp*	*Cpk*	*Non-conformance (PPM)*	*Minimum*	*Maximum*	*USL*	*LSL*	
1												
2												
3												
4												
5												
6												
7												
8												

Table 5.1: *A Capability Forecast*

Figure 5.4 displays a generated capability forecast template to be completed by the manufacturing engineer. The table allows the insertion of previous specifications and resultant capability performance where available, in addition to future forecasts, process limitations and the specifications required to ensure a Cpk of 1.33. Additional comments, qualitative information and general manufacturing rules can be added within the template.

5.2.4 Activity 3- Review Manufacturing and Inspection Issues of Release

This activity enables the integrated team to review the model for release and assess manufacturing capability for every feature and requirement. This is an iterative process, to be undertaken for every stage of definition. The activity is broken down into three stages: (1) Plan the review, (2) Conduct the review and (3) Assign follow-up actions.

1. **Plan the review**

   Each progressive release stage is subject to a formal design review on the date defined within the release plan. The compulsory attendees at the review are the required signatories for approval of that specific stage of release. The review may also include other experienced individuals involved with the release, including shop-floor operators, additional manufacturing engineering representatives or inspectors, as an example. Agenda items should include:

   - A review of the design definition
   - A manufacturing capability review and forecast
   - Manufacturing Engineering drawing issues
   - Point-by-point negotiations and action delegation
   - Conclusion and assessment of ongoing action

2. **Conduct the review**

   To ensure that every feature on the model is positively accepted or bought-off, a list of all features and requirements on that model should be compiled by the manufacturing engineer (Figure 5.5). This should contain the feature identification, the target and Upper Specification Limit/ Lower Specification Limit (USL/LSL values) as specified on the design, and a positive or negative (green/red) confirmation of acceptance. Before release of the master model, all features on the list must have positive (green) confirmation from the Manufacturing Engineer.

	A	B	C	D	E	F	G
1							
2		Feature Specification	Drawing Location	Target Value	USL	LSL	Manufacturing Acceptance?
3							
4							
5							
6							
7							

Table 5.2: *Comprehensive feature and requirement log*

The Design Engineer should present a review of product requirements, function and critical features on the model, identifying key similarities with previous products of the same component family and justifying tolerance allocation. The Manufacturing Engineer should then present a review of manufacturing capability and previous lessons learnt in addition to future forecasts based on predictions, modelling and new methods of manufacture.

The Manufacturing Engineer then reviews all issues by feature preventing acceptance with the released model. For each issue, the ME must state the reason for rejection and the changes required for acceptance. All issues raised are listed in a manufacturing issue database (Figure 5.6). Changes are either accepted or rejected with reason and justification, and on-going issues requiring resolution must be assigned an agreed resolving action.

	B	C	D	E	F	G	H	I	J	K	L
1											
2	Feature Identification	Drawing Location	Reason for Rejection	Originator	Change Requirements	Design Statement	Design Decision	Further Action to Closure	Action Owner	Date for Closure	Closure Confirmation
3											
4											
5											
6											
7											
8											

Table 5.3: *Manufacturing Issue database*

The manufacturing issue database tracks all raised model issues until closure and manufacturing acceptance and records an issue by:

- The feature identification and location on the drawing
- A short summary of the issue and change requirement
- The design response and decision
- Any further action required to closure

3. Assign follow-up actions

All items from the manufacturing engineering list of issues that were not agreed upon during the design review should be classified in order of priority based on 'Red-Amber-Green' or numeric scoring. Priority is given to issues that affect the sign-off of a feature or require substantial action to reach a resolution. Each on-going issue is assigned an 'action owner' and timescale for completion or further review. For major problems in resolving an issue, an escalation plan should be defined to ensure that the problem is directed to the most appropriate personnel.

5.2.5 Activity 4- Agree Progressive Release

This activity describes the correct company procedure for formally agreeing a progressive model release. As the progressive release stages advance, the feature and requirement list shall expand as the drawing becomes more defined and more items are added. The nature of release requires some items to be bought off in advance to others, dependant on subsequent design activity and manufacturing scheduling requirements.

The review plan states all features that require acceptance at each stage to allow progression to release. These must all be green before that release is issued. Once this has been achieved, the model can undergo final approval by all required signatories and confirmed for release through the company release procedures.

5.2.6 Activity 5- Finalise Master Model Definition

This activity ensures the final and complete manufacturing acceptance of all drawing features and requirements for final release of the master model.

- Every feature and requirement on the ME feature and requirement list must be accepted before master model release;

- Every issue on the ME issue database from each release stage must be confirmed as closed and resolved before master model release.

Once these points are confirmed, the final master model can be released. This release signifies the final freezing of alterations to the design, allowing progression to production. It is the responsibility of the model definer to ensure that all alterations agreed during buy-off are included in the final mode before circulation to the core team for final agreement. Approval by each function signifies that the content of the master model is achievable by that function.

5.3 IDEF0 Model

Prior to populating the process route-map, the information gathered was used to model the process using IDEF0. This modelling methodology breaks a process down into sequential, structured levels of information, explicitly identifying the inputs and outputs to each activity and the mechanisms and controls that govern it. Figures 5.4-5.8 show the formulated route-map in IDEF0 format achieved through analysing and filtering the information captured.

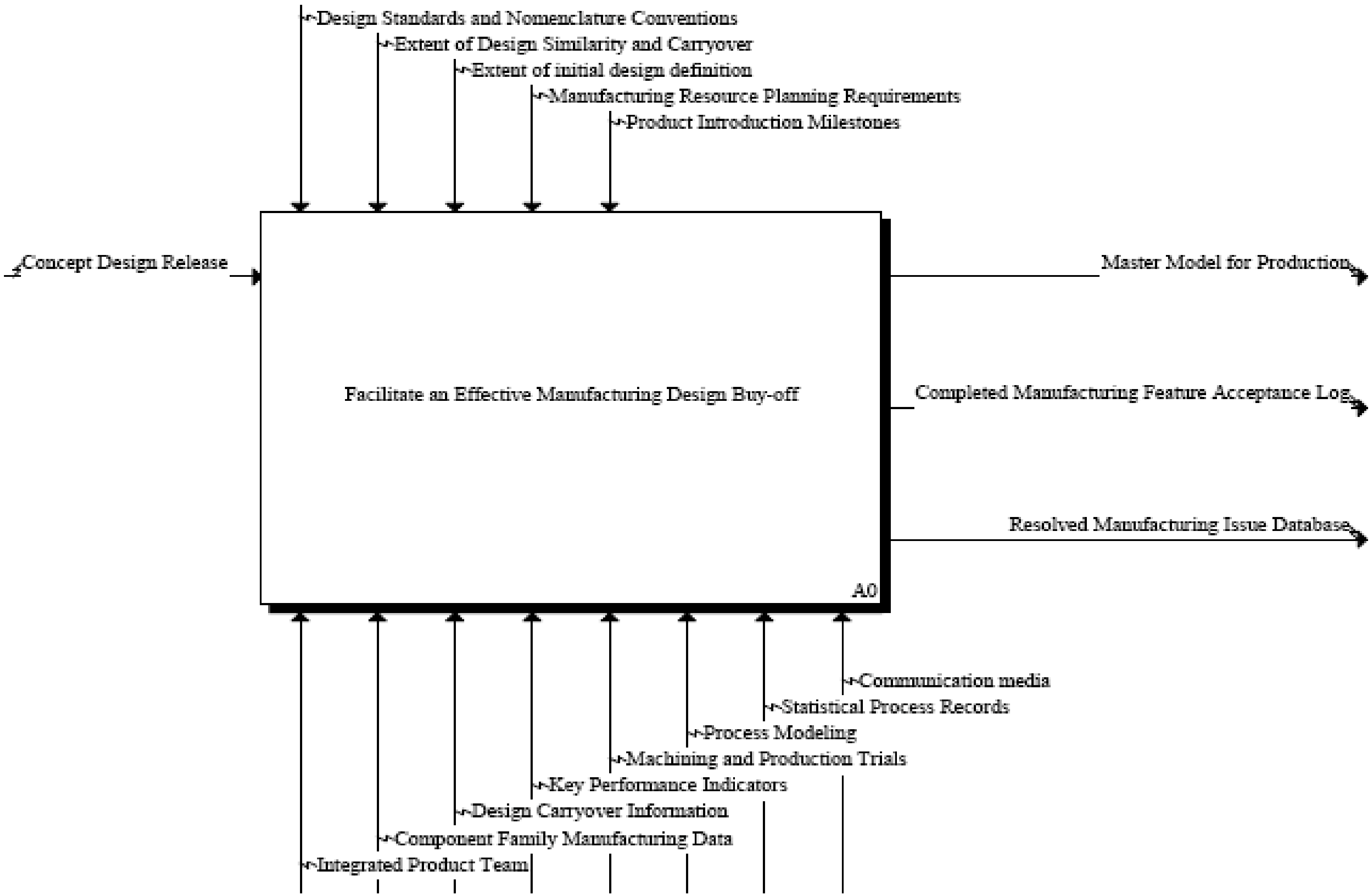

Figure 5.4: *Level A0: Facilitate an Effective Manufacturing Design Buy-off*

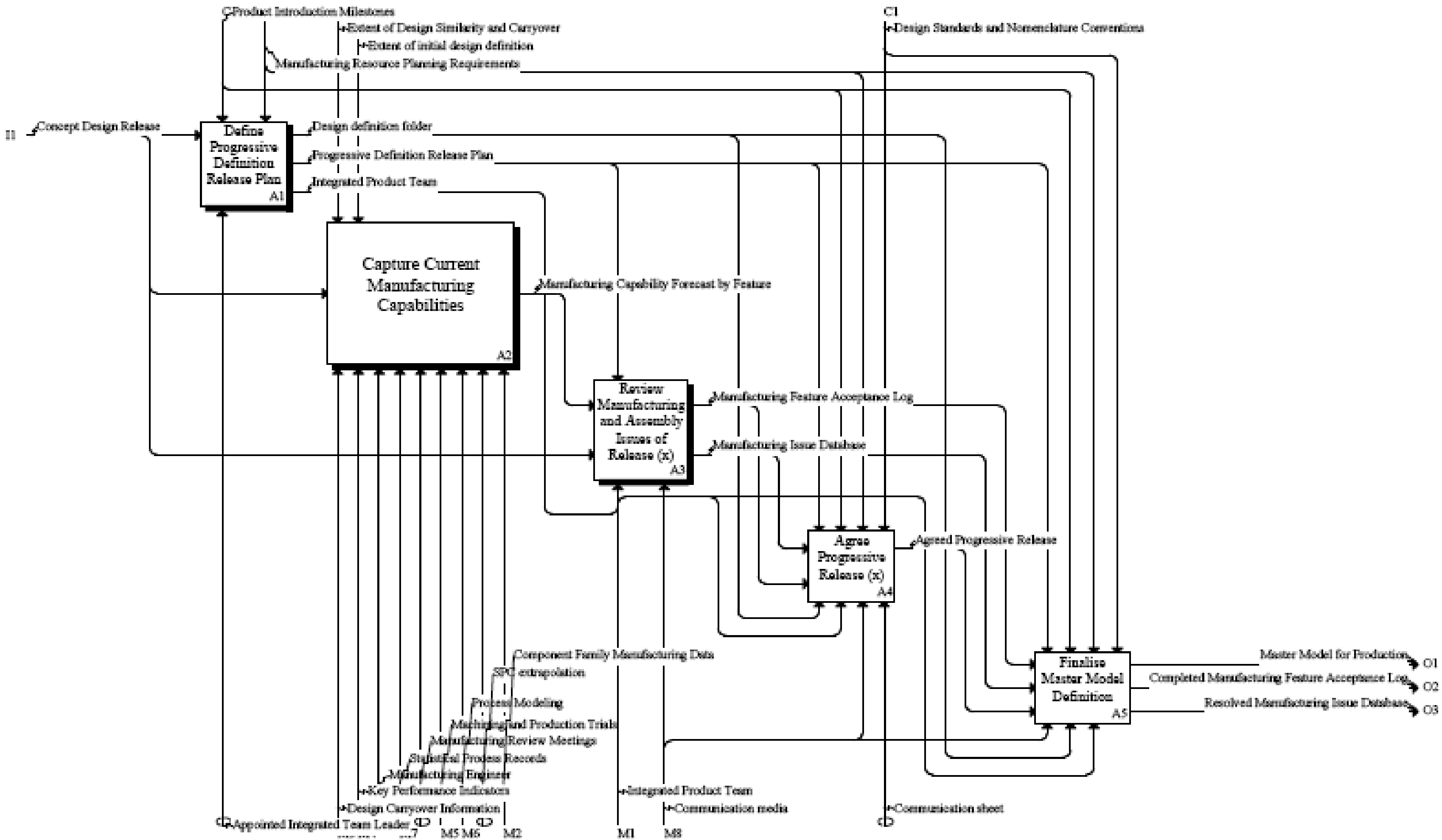

Figure 5.5: *Level A0 dissected to the five principle activities*

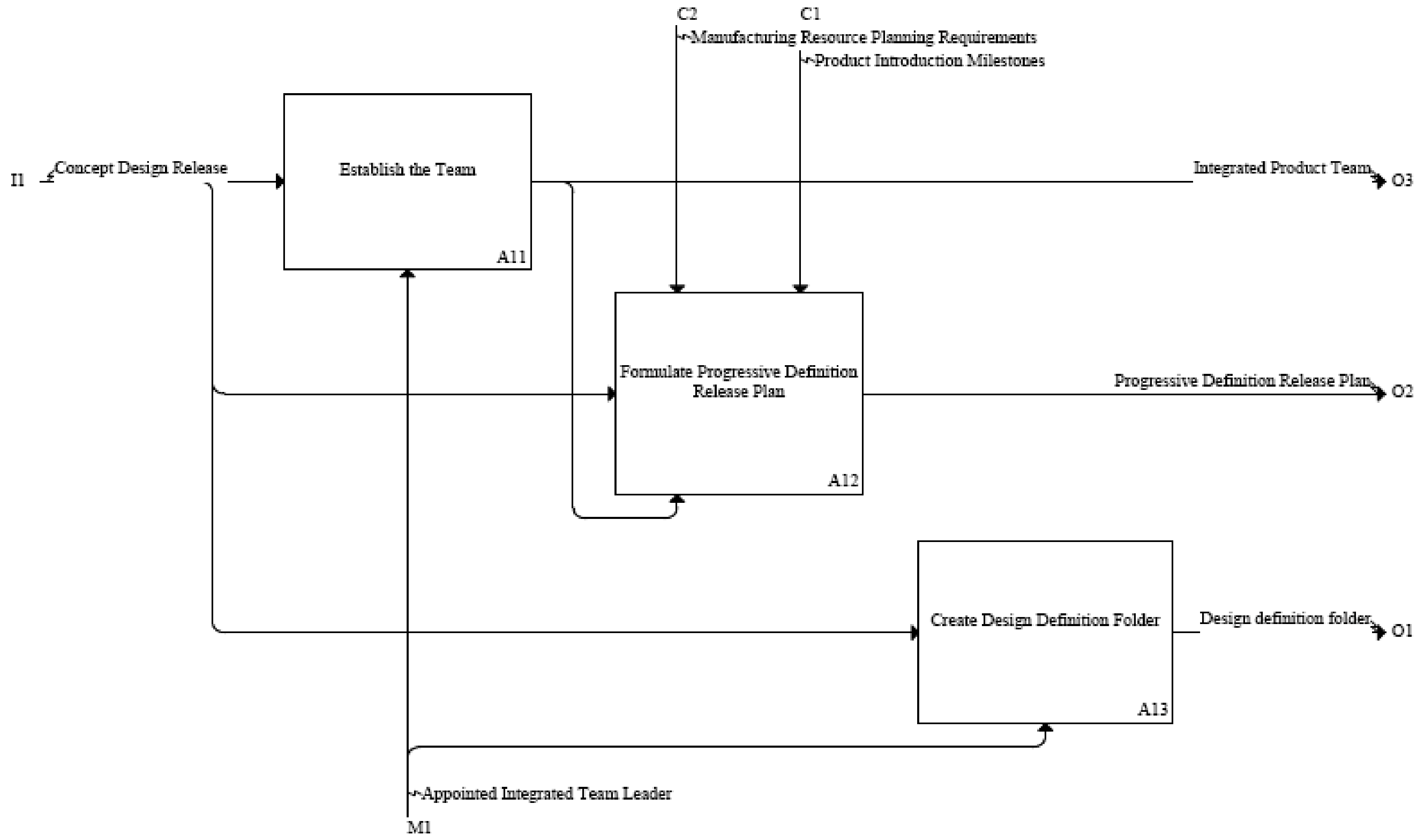

Figure 5.6: *Activity A1: Define Progressive Definition Release Plan*

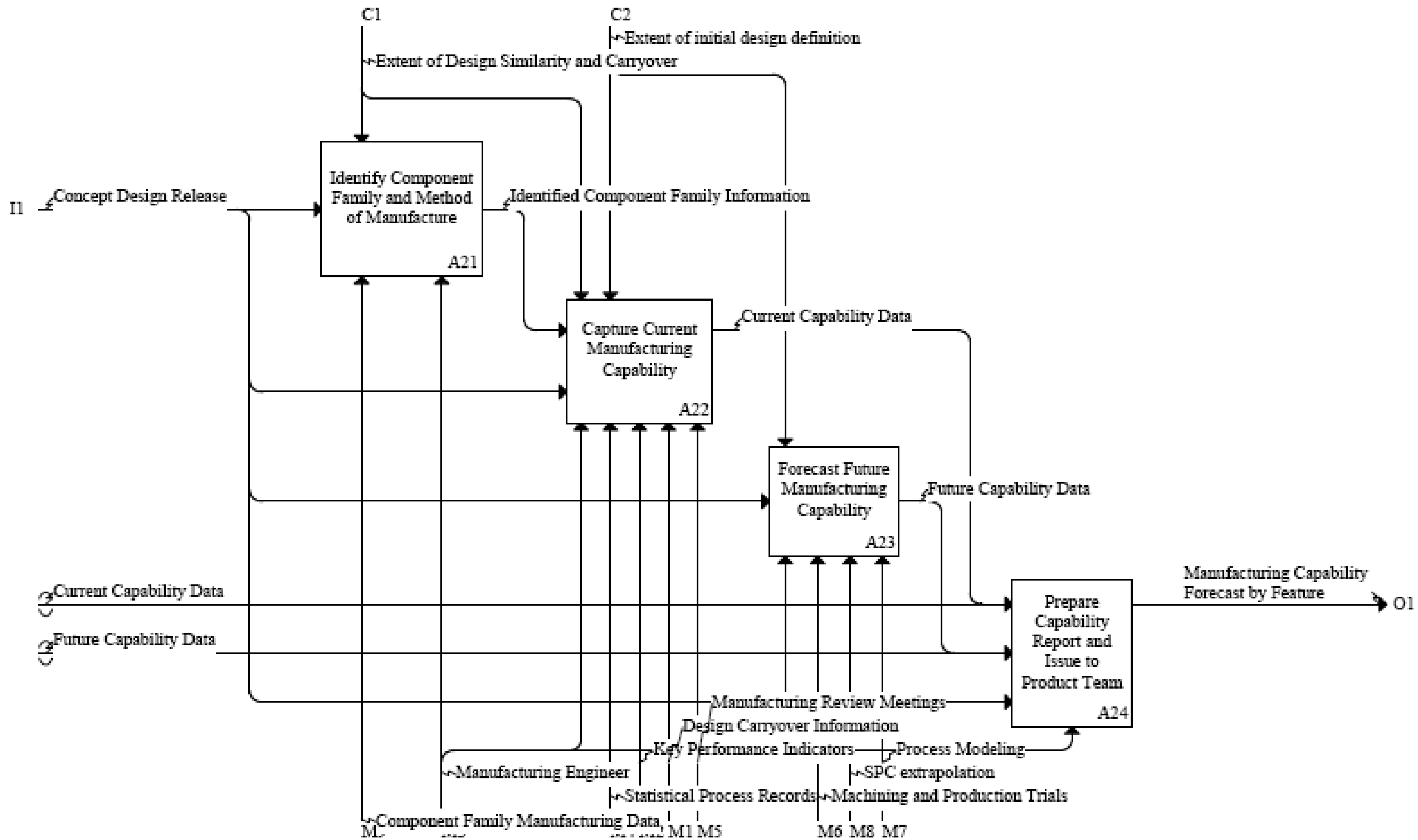

Figure 5.7: *Activity A2: Capture Current Manufacturing Capability*

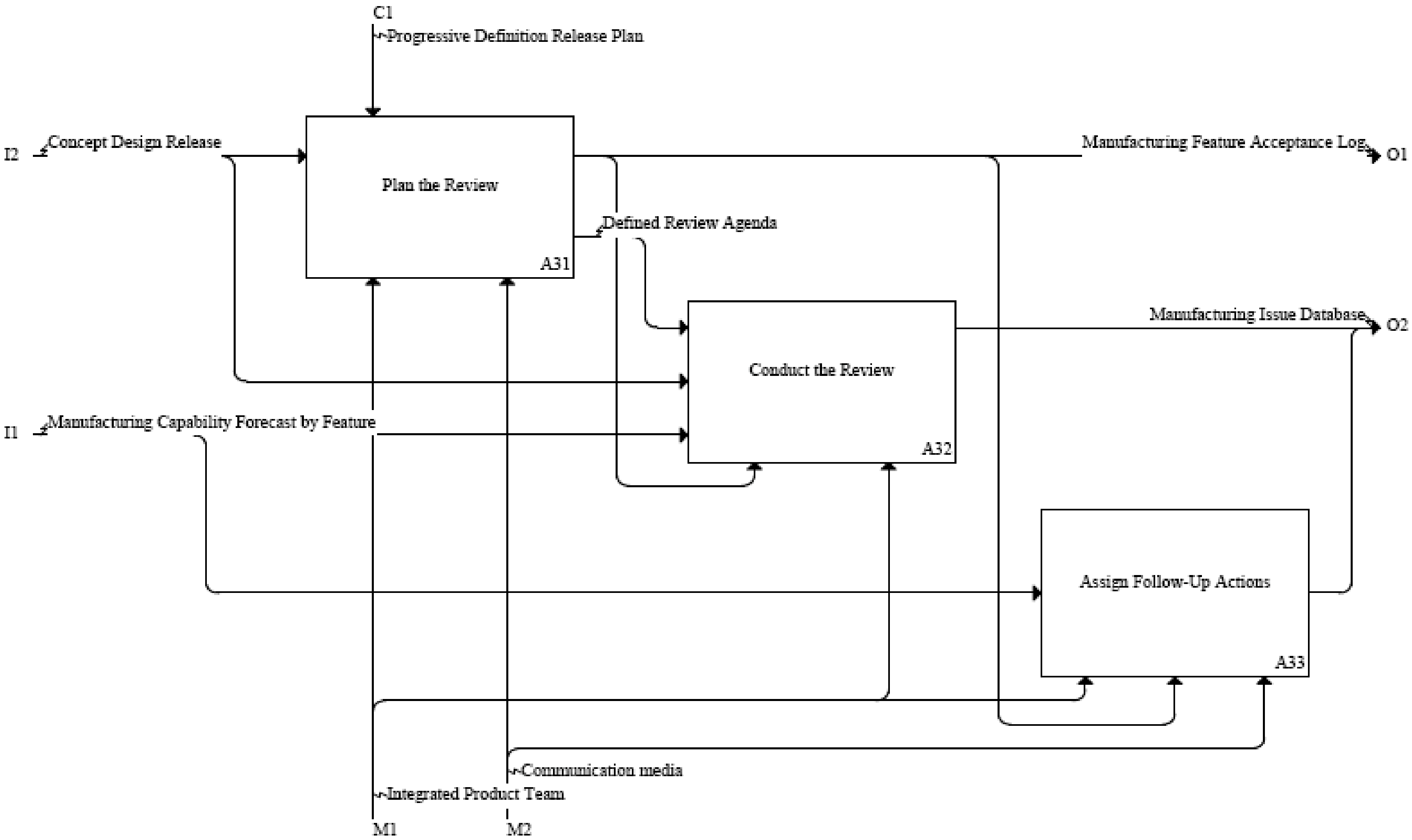

Figure 5.8: *Activity A3: Review Manufacturing and Inspection Issues of Release*

5.4 Summary

This chapter has explained the progressive definition process route-map that formed the manifestation of this research project as the main company deliverable. Each of the five defined activities required to facilitate an effective model release are dissected and their purpose and content explained. The route-map was built up on the requirements identified during the analysis of current practice, and promotes effective knowledge and information sharing at all stages of design definition.

In addition, specific templates are provided to portray quantified feature-by-feature capability data, in addition to tracking acceptance and manufacturing issues raised during buy-off. The next chapter describes the methods taken to provide final validation of this framework and integrate it within company operating procedures.

6 FRAMEWORK VALIDATION AND INTEGRATION

6.1 Introduction

The success of new concurrent engineering initiatives is defined primarily by the enhanced experiences of the end user and the ease of integration into current practices. Throughout the creation and development of a procedural framework, it crucial to authenticate the content with the company employees and ensure that their requirements are met. This chapter addresses the measures taken to build and validate the process route-map.

Continuous development of the process was undertaken through a focus on three case-study component plants. Within these plants, semi-structured interviews based around the key process activities were posed to the manufacturing engineering teams to expand the content based on real, contextual model releases. Upon final validation of the framework, an integration strategy for embedding the solution into standard company practice was defined.

6.2 Continuous Development

The company process requirements identified through the AS-IS evaluation of current practice formed the foundations on which to construct the process route-map. During this stage, three case-study component plants were selected as focus points on which to build the framework in the context of real applications and procedures used for buy-off. These were the Turbine Blade Facility (TBF) and Rotatives department, both located in Derby at the company headquarters, and the Front-Body Housing (FBH) plant located in Barnoldswick.

These particular components were selected on account of their vast differences in terms of complexity, production volume and functionality to serve as an unbiased representation of the differences across company manufacturing operations. Studying such contrasting components, each with different methods of manufacture, machining and production lead-times, aids not only in highlighting all of the different considerations required to produce a generic framework, but also exposes variation in procedures of progressive model release and capability process control followed within different facilities. Throughout phase 3 of the research methodology - solution development - a series of further interviews and workshops within the selected component plants ensued in parallel to the evolving framework in order to populate key activities with more specific information and best practices.

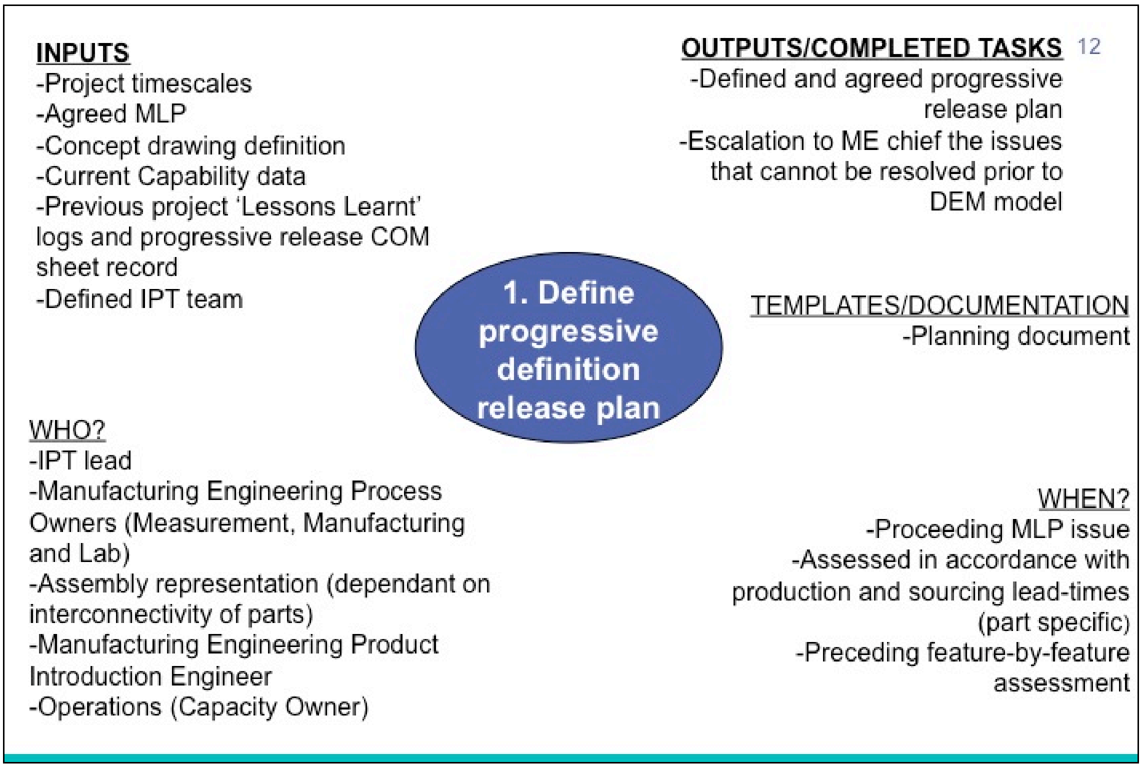

Figure 6.1: *A sample workshop slide*

Figure 6.1 shows a sample slide from a plant workshop and interview session. By presenting the top-level route map, questions were posed around each activity based on a number of principle descriptors, primarily the inputs and outputs to the task, assessing who is involved at each stage, when the stage should occur and any relating documentation to the process. Through incorporating the results from each interview into the following workshops, the information could be validated as the process went along, either by being further agreed upon or deemed biased and inapplicable to the latter interviewees and plants, thus removed. By revisiting each plant as the solution became more defined, validation of all input was incorporated as the solution was developed.

6.3 Final Validation

For final validation, the ten principle contacts involved with the research were revisited with the completed route-map and the process was dissected step-by-step to ensure agreement and make any final changes. Validation was undertaken with both the functional representatives (to secure integration with company procedure) and also with the specific component introduction teams (to ensure usability and case applicability). A few minor corrections were identified and amended before the final fixing of the solution. The route-map was accepted as a consolidation of all best practice into a structured process for application across the company.

This research project, the subset of a larger initiative, coincides with one of the key milestones in the product introduction of the Trent XWB (X-tra Wide Body) engine, the revolutionary new engine designed for the Airbus A350 XWB family of aircraft. The completed framework was integrated on to the RRPS in time for commencement of stage 2 design activity on the product introduction landscape the finalised framework was carried forward upon completion for implementation within a series of both design buy-off workshops and product definition meetings as part of a continuous improvement initiative.

6.4 Summary

This chapter has described the interviews and workshops held in order to validate the progressive release process route-map within the context of the company requirements and related procedures. In addition, the methods taken to integrate the route-map into the company intranet and design release meetings are described. The following conclusion chapter evaluates the findings of the thesis project, summarising the major achievements and benefits resulting from the research.

7 DISCUSSION AND CONCLUSIONS

7.1 Introduction

This research project has developed a current capability design for manufacture framework based upon the identifications of inefficiencies within the preceding practice of model definition and release of a design and the assessment of best DfMA practice. This chapter presents a concluding assessment of the research project undertaken and the principle results and benefits that emerged from the formulation of the solution.

Following a brief evaluation of the research progression and methodology followed, the principle outcomes and benefits from the achieved results are summarised. The contribution to knowledge made is then assessed based on both the fulfilment of the original problem statement and the knowledge gaps identified within the literature review. The applicability and limitations of the research outcomes within the wider research field are discussed before the thesis is concluded with recommendations and discussion of potential future and related research opportunities.

7.2 Methodology Discussion

The four-stage qualitative research methodology adopted during the project proved successful in capturing the required information to populate the solution framework and reach all of the objectives defined at the project initiation. The literature review undertaken succeeded in identifying the primary considerations to be taken into account when establishing a DfMA framework, highlighting the importance of process capability knowledge and providing a number of academic and industrial case studies to place the ideas in contextual scenarios. This was complemented by the benchmarking study, which analysed the effectiveness of different practices of progressive product definition across a number of different automotive and aerospace companies.

The adoption of qualitative, semi-structured questionnaires put to representatives across business functions and externally during benchmarking proved an efficient means to capture the information required to build the solution framework. Questions posed were built up around the specific requirements of each stage of the research progression, from assessing the methods of current practice and identifying improvement opportunities to specific, activity based questions as the framework took shape. The extensive range of contacts consulted permitted the minimisation of bias and the identification of generic information. Finally, complete validation with expert opinion ensured that the company expectations had been met with the completed framework. The integration and implementation strategies defined assisted in making the process available and apparent to company employees for immediate use in further progressive product definition.

The principle limitation of the adopted methodology was the lack of any quantitative analysis. Although deemed out of scope for the project, a numerical method of assessing and rating the effectiveness of practices adopted across the company and, particularly, during the benchmarking analysis would have permitted a more quantified assessment of their effectiveness.

7.3 Results and deliverable discussion

The aim of this project was to create a current capability design for manufacture framework in the aerospace industry. This aim was achieved through the adoption of a four-stage qualitative research methodology to achieve the four principle objectives as set out at the commencement of the project:

- *Investigate DfMA principles and process capability analysis through a comprehensive literature review;*

  This objective was achieved through the consultation of over sixty academic and industrial sources to identify and profile the key considerations required when introducing a DfMA initiative.

- *Capture the AS-IS practice of progressive drawing release in the aerospace and automotive sectors;*

This objective, achieved through the benchmarking analysis and company interviews, succeeded in profiling current practice of progressive model definition and assessing the key considerations and best practices followed both across the different company functions and externally. Through the analysis of past case study releases, the problem statement was better defined based on the inefficiencies and issues previously encountered.

- *Create a route map of the release process built around the optimal critical path, defining roles and procedures to follow at each stage;*

  An interactive process route-map detailing the progressive definition and release of an engineering model was created via a series of five key activities. Each activity can be dissected further into sequential levels of information that inform the user of the exact procedures and information requirements to successfully carry out that activity. The route-map was established and built up through a series of semi-structured interviews and workshops undertaken within three component manufacturing plants selected as representative case-studies from which to collect the required information and knowledge required to populate and structure the information required to carry out each activity.

- *Validate the proposed process framework through expert opinion.*

  A detailed validation procedure with expert opinion was followed on the created process route-map. Ten principal project contacts from across different functional departments and job roles were re-consulted at the completion of the framework. The process was broken down by each activity to ensure agreement and completeness of all the information contained within.

7.4 Contribution to knowledge

The principle contribution to knowledge made by this research project was the amalgamation of DfMA principles and process capability knowledge into the creation of a tangible process to facilitate the progressive definition and release of an engineering model for production. This framework was founded on an analysis of the current practice of product definition and development across the aerospace and automotive sectors and promotes the identification of:

- The major stages and activities within the progressive release of a model in order to support manufacturing production planning;
- The individuals and functions involved within each activity and their requirements and roles in supporting the evolving model;
- The capability information and knowledge required to optimally carry out each activity through informed design.

7.5 Wider applicability and limitations

This framework produced by this research was designed to be generic to the company, and thus applicable to all instances of model release and buy-off across all commodity units and manufacturing units. Although the specific information defined in the framework is largely company specific, the principles and structure identified are applicable to other manufacturing applications, particularly within the aerospace and automotive sectors that deal with similar complexity products and methods of design.

Given the time constraints of this research, the solution was based around three contrasting case-study component plants, out of a possible fourteen that make up the company. Although this was deemed sufficient to produce a broad and unbiased data set, the inclusion of additional component units, if possible, would have added further strength to the framework and likely identified new considerations and areas of best practice in model definition.

The benchmarking assessment undertaken was fairly modest, also on account of time constraints and the difficulty in achieving positive responses for participation. Although the assessment added value to the research and identified some useful cross-sector best practice, an expansion would have been beneficial in collecting a larger information set.

7.6 Conclusions

Delays and setbacks often arise within high-complexity aerospace product development processes due to a lack of structure and adequate communication between design, manufacturing and assembly functions during the progressive release and buy-off of an engineering model. Manufacturing functions frequently lack a quantified, effective means of portraying their production capabilities to the design function for consideration in product design, and, as a result of this, a large amount of time and resources are spent amending designs that have encountered problems on progression to production.

This research proposes a framework to address the identified issues, facilitating optimal Design for Manufacture based on current manufacturing capabilities. The produced process route-map structures the progressive definition and release of an engineering model, promoting the incorporation of specific feature process capability knowledge within the design and definition of a product and defining a specific methodology to structure communication and correct planning within each application. Adherence to the process route-map ensures that no engineering model is released that cannot be realised by manufacturing and assembly functions.

7.7 Further work

There is potential for considerable benefit in the creation of case-specific frameworks for each component plant. This would allow the incorporation of specific procedural guidelines and timescales pertinent to each context of production. The concept of this research project could also be expanded for application within different companies and industries. Contrasting product and volume manufacturers operate under completely different organisational structures, and thus would identify different priorities and requirements from the formulation of such a framework.

Relating to the limitations identified within this research, an expansion on the benchmarking analysis, particularly concerning methodologies for capturing and using process capability data in early design, would form a beneficial contribution to knowledge. This could allow a direct, quantitative analysis and measurement of the benefits and reductions in design lead-times and iterations achieved through the effective use of process capability data.

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APPENDICES

Appendix I- Internal Questionnaire (Manufacturing Engineer- Turbine Blade Facility)

The following is a sample of one of the range of internal questionnaires posed to employees involved with the progressive drawing release.

Each visitation required some personalisation and addition to the question set based on the component plant and individual subject to interview. The semi-structured questionnaire style was used in face-to-face interviews only. No copies of this questionnaire were distributed for personal completion.

Introduction

Interviewee Name……………………………………..………………………..…
Job Title ………………..…..………………………………………………….......

Can you describe your key responsibilities within product design and realisation?

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What are the key functions of the department within which you work?

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Which individuals and external functions do you principally interact with in order to carry out your job?

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Progressive drawing design release

How is the release of a new engineering product drawing defined and managed within the product introduction process within your component plant?

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What are the key milestones that you work toward?

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By what media are communication and design negotiations captured during this process?

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Capturing manufacturing capabilities

At what stages of component design do manufacturing and assembly capabilities come into consideration within your facility?

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To what extent is design and capability information carry-over from previous product models utilised?

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'Lessons Learnt' and statistical process capabilities

Is there a formal process for capturing Lessons Learnt across different functions within your component plant? How are these lessons inputted and categorised?

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Do you operate key milestone reviews or regular meetings to assess Lessons Learnt and best and worst practice experienced on a project?

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How are Lessons Learnt made accessible to the workforce within the component plant? What implementation strategy is in place to drive these lessons back into future processes?

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How is Statistical Process Control data displayed and considered during product design?

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Do you define key characteristics or 'Critical Features'? How are these treated and managed?

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How are more tacit, qualitative manufacturing 'rules' and inherent capabilities captured and portrayed to design?

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Can you describe any major or recurring problems resulting from current practices of progressive design release and buy-off?

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Is there anything else that you wish to add or discuss?

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Thank you very much for your time

Appendix II- Benchmarking Questionnaire

The following is a sample excerpt of the generic benchmarking questionnaire used during external company visitations. The title page (detailing the location, company and data of interview) has been omitted in the interest of privacy, as have the introductory pages explaining the project aims and research statement.

Each visitation required some personalisation and addition to the question set based on the company and individual subject to interview. The semi-structured questionnaire style was used in face-to-face interviews only. No copies of this questionnaire were distributed for personal completion.

Today's visit

The primary purpose of today's visit is to discuss practices of New Product Introduction within **** and how manufacturing capabilities are taken into account during the progressive release of a design.

I, Angela Whiteside, would like to thank you for your time given for today's discussion. All information provided shall be treated with the strictest confidence and not directly quoted or passed on to third parties.

This semi-structured questionnaire shall begin with some general questions concerning your job responsibilities and role within product realisation. Some more specific questions shall then be asked concerning practices followed within ****.

Introduction

1) Interviewee Name……………………………………………..…………..…
2) Job Title ………………..…..………………………………………….....
3) Years within the company…………………………………………..…...
4) Previous experience and career history……………………..……..………

5) What is your role within ****?
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6) What department do you work under? What are the key functions of that department?
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7) Which individuals or functions do you principally interact with in order to carry out your job?
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Progressive drawing design release

8) How is the release of a new engineering product drawing defined and managed within the product introduction process at ****?
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9) At what stages of the overall product introduction process does the design release and buy-off begin and end? What are the key milestones?

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10) What individuals or functions are involved throughout the stages of release and buy-off of a design? What inputs do they bring?

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11) By what media are communication and design changes captured during this process?

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12) Can you describe the primary causes of delays or problems with the progressive release of a design to production functions?

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Capturing manufacturing capabilities

12) How are manufacturing and assembly capabilities taken into account throughout the design process?

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13) At what stages of design do manufacturing and assembly capabilities come into consideration?

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14) To what extent is design and capability information carry-over from previous projects utilised?

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15) How and by what media do these parties convey and communicate their capabilities to design?

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'Lessons Learnt' and statistical process capabilities

16) Is there a formal process for capturing Lessons Learnt across different functions at ****? How are these lessons inputted and categorised?

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17) Do you operate key milestone reviews or regular meeting to assess Lessons Learnt and best and worst practice experienced on a project?

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18) How are Lessons Learnt made accessible to employees of ****? What implementation strategy is in place to drive these lessons back into future processes?

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19) How is Statistical Process Control data displayed and considered during product design?

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20) Do you define key characteristics or 'Critical Features'? How are these treated and managed?

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21) How are more tacit, qualitative manufacturing 'rules' and inherent capabilities captured and portrayed to design?

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22) Are manufacturing capabilities incorporated into your CAD systems and software? If yes, in what form?

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23) How are parametric design tolerances displayed and justified by design?

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Is there anything else that you wish to add or discuss?

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Thank you very much for your time