Cranfield University

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A Framework Relating Producibility Problems to the use of Manufacturing Information in Design

School of Industrial and Manufacturing Science

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ABSTRACT

A Framework Relating Producibility Problems to the use of Manufacturing Information in Design

by Michael John Gregory

This thesis presents the development of a framework for relating the reasons for problems of producibility that occur in manufacturing to the sources of information available to designers. Advice and guidance on Design for Manufacture was obtained from textbooks, journal articles and conference papers that sought to improve the process or report on design-related difficulties in manufacturing. Industrial experience was gained from a two-year project in defence aerospace, researching concurrent engineering in the extended enterprise. Examples of good practice across a range of industries were gained from interviews with practitioners, with advice both from customers engaged in design and from manufacturing suppliers. Further industrial experience was provided by two studies of civil aerospace, covering in-house and outsourced manufacture. Potential problems were classified and then related to the sources of knowledge available to prevent these problems reaching the shop floor.

The detailed analysis of findings is presented and provides a structured approach that could assist in planning concurrent engineering processes, especially communications and teamworking. This would enable potential producibility problems to be addressed in a comprehensive manner so as to minimise the costs, effort and delay associated with them. It would also encourage opportunities for improvement to be promoted at the earliest stage in product development, where they are the most effective.

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CANDIDATE

Career History

Served as an engineer in the Royal Air Force from 1958 to 1996, joining as a Technical Cadet. Read Mechanical Sciences at Cambridge University and later completed an MSc in Aviation Electronics at Cranfield University.

Experience includes: maintenance support for operational aircraft and ground electronics systems; introduction into Service of new military aircraft, including one year at a factory site and several years' headquarters project management; the design, manufacture and installation of specialist avionics in aircraft; engineering management IT systems; Engineering Sponsor for RAF flight simulators; training of engineers; wet-film and digital image processing.

Cranfield University since 1997 as a researcher on the AEROEXTN Project, and subsequent work to complete this thesis.

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LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
ATP	Authority to proceed
AXP	AEROEXTN project
BOM	Bill of materials
BPS	Best practice study
CAD	Computer aided design
CADDS 5	CAD software by Computervision (now part of Parametric Technologies)
CAE	Computer aided engineering
CAM	Computer aided manufacturing
CAS	Civil aerospace study
CATIA	CAD software by Dassault Systèmes
CE	Concurrent engineering
CERC	Concurrent Engineering Research Center (set up by DARPA)
CIM	Computer integrated manufacturing
CMM	Coordinate measuring machine
CORBA	Common object request broker architecture
CPD	Continuous product development (team)
DARPA	(US) Defense Advanced Research Projects Agency
DFM	Design for manufacturing
DMS	Document management system
DST	Decision support tool
EDI	Electronic data interchange
EDN	Electronic design notebook
EIS	Engineering information system; Entry into service
ESI	Early supplier involvement (with Design) = SIL
GD&T	Geometric dimensioning and tolerancing
ICAD	Intelligent CAD, a proprietary knowledge-based CAD system
ICY	Interchangeability (precision machining for interchangeable parts)
IGES	Initial graphics exchange specification
IPD	Integrated project development; Integrated product development
IPR	Intellectual property rights
IPT	Integrated project team
ISS	Information-sharing system
ITP	Instruction to proceed
JV	Joint venture

KBE	Knowledge based engineering
KFD	Key features diagram
MI	Manufacturing information
MTBF	Mean time between failures; Mean time before failure
NC	Numerically-controlled, e.g. machine tool controlled by computer
NIST	(US) National Institute of Standards and Technology
NP	New product
NPI	New product introduction
OEM	Original equipment manufacturer
PC	Personal computer, e.g. IBM or clone
PDM	Product data management; Product document management
PI	Producibility interaction
PLC	Public liability company
QA	Quality assurance
R & T	Research and technology
RFQ	Request for quotation
SIL	Supplier in the loop (with Design) = ESI
SIL-CE	Supplier in the loop concurrent engineering
STL	Stereolithographic
SMEs	Small and medium enterprises
SOP	Start of production
STEP	Standard for the exchange of product model data (ISO 10303)
TQM	Total quality management
UPC	Unit production cost
VNC	Virtual numerical control, software to simulate machining
WQN	Works query note

Chapter 1 Introduction

video meliora proboque, deteriora sequor.
"The better course I see and do approve, the worse I follow." (Ovid c.20 BC)

1.1 Overview

A wide range of design models and methods, training courses, standards, procedures, specifications, reports, textbooks, computer-aided design (CAD) systems, design for manufacture (DFM) databases and tools is available to designers, and concurrent engineering (CE) practices have been widely publicised and adopted by industry, with emphasis on teamworking and collaboration. Many improvements have been made compared with the earlier practices, whereby each party in the chain worked sequentially and in isolation, throwing the drawings 'over the wall' from Design to Procurement to Production Planning to Manufacture to Inspection to Assembly. It is now widely accepted that Design should encourage the early involvement of other disciplines so that changes can be made to avoid later difficulties and also enable positive suggestions to be embodied before the design is complete and changes become costly or impracticable. However, empirical evidence suggests that manufacturing 'problems' still exist.

This thesis describes the research undertaken to find out why problems should occur in the manufacture of individual piece parts for the aerospace industry. The aerospace industry has an annual turnover of £18 billion, 151,000 employees, and a positive contribution to the UK's trade balance of £3.8 billion (Society of British Aerospace Companies' year 2000 data). Problems may either follow from the design not being best matched to the processes and materials used, or because the manufacturing instructions do not adequately convey the design to those on the shopfloor responsible for interpreting them and making the parts. The results of this research are presented in the form of a framework that identifies the types of reasons for such problems, the sources of information and influence available to designers to prevent them, and the factors that contribute to the reasons and relate them to the sources.

Development of the PhD research question began with the author's involvement as a researcher on the AEROEXTN project. This was a two-year longitudinal study of CE across the supply chain in the aerospace defence industry. The project involved setting up and running the SESAME live pilot project for the design and manufacture of missile parts. The AEROEXTN project began with a study of 12 prime-supplier pairs across a range of industries. This study was undertaken using on-site interviews to learn about current best practice in CE. At the same time an initial study was made of the relevant published literature. Workshop sessions with the industrial collaborators were held to distil practical issues from these studies, and the subject of producibility (or manufacturability, involving matching product to process) was accorded the highest priority. An integrated project team comprising the customer, manufacturing supplier and university researchers was formed to identify and resolve issues of producibility during the SESAME pilot. The author was responsible for developing a Producibility Interaction model that was used as the basis for structuring the team discussions. This CE dialogue involved 13 DFM issues and analysing their characteristics.

On completion of the AEROEXTN project, so as to obtain a broader base of case study material for the PhD research, the author used the PI model as a tool to investigate problems in the manufacture of other parts in the civil aerospace industry. The author conducted on-site studies with two major UK aerospace companies to cover both internally sourced aluminium parts and outsourced titanium and composite parts. He interviewed separately representatives of Design, Manufacturing, Quality and Purchasing to compile reports that were then reviewed collectively. A total of 25 further DFM issues were documented and analysed.

The AEROEXTN and the civil aerospace studies led the author to appreciate what was involved in setting up and running a CE project, including the priorities, tasks, issues and enablers, barriers, and benefits. While managers understood the principles and benefits of CE, the implementation issues seemed not to be readily apparent to them. Hence a whole range of producibility problems could arise, despite the availability of CE and DFM techniques that should ensure designers have access to information to prevent them. The focus of the PhD research was then directed towards examining why such information was not used to greater effect.

The author believes that the prime responsibility for producibility lies with design. Lack of optimisation may result in a design that is difficult or impossible to make with the specified process, or a part that could have been made better (e.g. more easily, quickly, with less scrap/rework, with cheaper tooling). Where problems occur because the design was not optimised for manufacture, it would be important to trace the sources of information available to influence the producibility of the design, and the designer's use of them. Whereas the number of potential producibility problems may be infinite, they may be classified as occurring for a finite number of types of reasons. Particular manufacturing problems from the industrial studies were used as units of analysis to explore the reasons, and were combined with a continuing research of literature to formulate a list of 35 types of reasons for such problems. These reasons were then grouped into five categories, based on subjects that could be recognised as representing the range of possible causes.

Similarly, while a vast quantity of information exists in the world, the number of sources available to influence the design of parts (including their producibility) is finite. Such sources were identified and formulated into five categories. Although these particular categories were not the only possible ones, they were selected with the intention of helping both the author and the user of the research to focus on both obvious and more obscure matters that were relevant. A two-dimensional matrix was constructed to show how the types of reasons could be related to these sources. This framework was populated with extensive citations from the literature to illustrate the factors that defined these relationships, and further examples were added from the industrial case studies.

'Communication and teamworking' was, at 47%, the category of sources of information for preventing producibility problems reaching the shopfloor that related to the greatest number of factors. However, any of the 91 factors in the framework, alone or in combination, could provide the key to avoiding particular problems. No attempt has been made in this research to prioritise the factors.

Recognition of these factors is an important step towards avoiding the problems, but no benefit will follow from falling into the trap Ovid reported (quoted under the chapter title above). It is important that all those involved in the design to manufacture chain should not only see the better course of action and approve of it, but that they should follow it. The factors identified in the framework suggest that soft issues such as leadership and motivation are just as necessary as the hard technical issues in achieving this.

1.2 Industrial Input to the Research

The AEROEXTN project was a 2-year contract funded jointly by industry and the UK Engineering and Physical Sciences Research Council, under their Innovative Manufacturing Initiative. The consortium partners had initiated the thinking that led to the project proposal to extend the benefits of concurrent engineering beyond their internal processes. They wished to embrace the expertise of the suppliers on whom they were increasingly relying for the production of parts. The objective was to develop processes by which competence in Concurrent Engineering could be applied to the Extended Enterprise with advantage to quality, time and competitiveness.

The AEROEXTN consortium consisted of: two major UK defence companies, MATRA BAe Dynamics and British Aerospace (BAe) Military Aircraft and Aerostructures; one small/medium enterprise (SME) aerospace supplier, Bellhouse Hartwell Ltd, Westhoughton; and two academic bodies, Cranfield University and the University of Luton.

BAe Chadderton and MATRA BAe Dynamics (Stevenage and Lostock) were the AEROEXTN industrial collaborators to pilot CE practices in a project called 'SESAME'. BAe Chadderton acted as an independent supplier of machined parts for guided missiles to MATRA BAe Dynamics, the prime contractor and customer. The prime contractor undertook design and systems integration at Stevenage, with assembly and test at Lostock. The supplier manufactured specific complex machined parts to the detailed CAD design of the prime. Bellhouse Hartwell were involved in discussions on the application of CE to SMEs, but took no direct part in the design or manufacture of SESAME parts.

SESAME demonstrated that it was possible to involve the supplier in the CE loop (SIL-CE) and benefit both customer and supplier – the 'win-win' solution. However, this needed the correct investment, planning and management to be successful.

The AEROEXTN project recognised the importance of producibility to the industrial collaborators. The 13 issues raised during the SESAME pilot showed that even an experienced senior designer could improve the producibility of his design when prompted by the supplier's producibility engineers. However, the spirit of mutual co-operation that had been carefully set up to foster teamworking and encourage the discussion of possible changes during this pilot project meant that most of the 'soft' issues that literature suggested might be barriers to limit producibility interaction were pre-empted. The result was to focus largely on 'hard' technical matters.

Further industrial case studies in a different environment might be expected to show a higher proportion of the soft issues. This was found to be so when, after completion of AEROEXTN, the author conducted two one-week on-site investigations at two major UK aerospace companies to examine producibility-related manufacturing problems in the civil aerospace sector. The first study showed that producibility problems had not disappeared when batches of a previously outsourced part, supposedly mature, were brought back to be manufactured in-house. Despite discussions with Design during the planning of manufacturing transfer, a number of problems were discovered on the shopfloor. The second study covered outsourced parts and the producibility problems that had been addressed between customer and supplier. A further 25 producibility issues were captured during these civil aerospace studies, bringing the total to 38.

The civil aerospace studies showed that similar problems had arisen in the areas covered by the SESAME pilot. However, a number of issues were related to human error and culture/social reasons that had been 'managed out' by the structured approach in SESAME. Particularly noticeable was the reluctance of designers to initiate changes that could compromise performance (e.g. departing from their ideal shape, or adding weight) where the production engineers had to argue the case for a compromise to ease manufacture. This often meant that such changes were not considered until detail design was complete, and only compelling cases could be accepted.

A comparison between in-house manufacture and outsourced supply showed that there was no clear-cut net advantage in producibility from having parts made in the company's own workshops. Although there were no contractual or intellectual property rights barriers to internal communication, and there was full compatibility of data transfer, there was still the problem of Manufacturing being a different department from Design. In some respects, the in-house function had less dialogue because they did not negotiate manufacturing contracts in the same way as an outside supplier. Conversely, the outside supplier would be given an incentive to share in the saving of costs from any changes they suggested to ease manufacture, and they may well be able to draw on their wider experience from supplying similar parts to other customers.

The success of CE in improving producibility appeared to depend on the way the processes were led and managed rather than whether or not they involved the Extended Enterprise of an outsourced design to manufacture chain. What was significant was whether designers used the sources of information on producibility that were available, and what reasons might prevent them from receiving or using such information effectively.

1.3 State of the Art

The literature was examined to supplement the interviews conducted with practitioners to determine the current state of the art of concurrent engineering principles, and DFM in particular. Examples were sought of:

- Successful applications;
- Tools to assist DFM;
- How designers obtained their knowledge of manufacturing;
- How production and manufacturing engineers communicated with designers;
- Problems occurring in manufacturing.

It was apparent that many tools existed to assist the CE process, but they were not always applied. There was no indication in the literature that information on producibility was in any way lacking, apart from concern that industry practice concentrated on filing reports of successful projects without recording failures. In some instances designers may need to request tests or trials to prove a particular process and material combination. However, it should normally be possible to initiate this at an early stage so that the results are available by the time they are needed to complete the design.

Published studies suggested that designers made only limited use of the sources of information available, often relying on their own experience and limiting consultation with others to their immediate colleagues. Management methods were available to promote the best practice in CE, e.g. to provide appropriate incentives for communication and teamworking. However, reports of dramatic improvements following their application suggested that the implementation of such methods is not currently widespread in industry. Managers might be motivated to act if they could fully appreciate the reasons why the available sources of information on producibility are not always used to prevent manufacturing problems reaching the shopfloor.

These considerations led to the formulation of the research question:

> "Why do manufacturing problems reach the shopfloor when sources of information are available to prevent them?"

1.4 Research Objectives

The research objectives are to:

- determine producibility issues;
- identify sources of information and influence;
- devise a framework for application to practical engineering environments;
- partially validate this framework, according to recommended case study research methodology.

The domain for this research is the design for manufacture of individual mechanical piece parts for the aerospace industry. This industry was chosen because of its importance to the national economy, the close ties it has with Cranfield University, and the author's previous involvement with this environment. Mechanical parts were chosen to avoid security problems – particularly in Defence applications – that could limit access to information or prevent its open publication. Piece parts, rather than assemblies, were selected to help focus the work on a field that was not too broad for the effort available.

1.5 Research Methodology

Various accepted qualitative methods were considered for this research. There is a vast amount of data in industry and in the published literature covering this broad area of concern. A 'Grounded Theory' approach was therefore adopted as the most appropriate method of developing a model to present and analyse the data that would best answer the research questions.

In qualitative research, the rigour and validity of the research is established in the design and execution of the research. The industrial validation demonstrates the relevance of the research results to practical applications. Because the research effort was directed at building the framework and validating it according to the methods used and the case studies, further work to apply the final framework to industry was left to future research. For this reason, the completed validation is described as 'partial'.

The grounded theory method was applied in the form of 14 action steps that: collected and discussed preliminary data; formulated the research question; developed concept categories for collecting further data; formed a framework for analysis; collected further data; analysed and presented the results.

1.6 Contribution to Knowledge

The particular achievements are:

- Identification of a comprehensive list of producibility problems in the research domain;
- Identification of the types of reasons for problems or missed opportunities in Design for Manufacture that may allow manufacturing problems to reach the shop floor;
- Identification of the sources of information or influence that could enable designers to prevent them;
- The development of a framework for application to practical engineering environments that shows the factors that relate the reasons for producibility problems to the sources of information that could have prevented them.

This approach is different from the published literature on Design for Manufacture and concurrent engineering. Published literature gives both general and specific guidance in a prescriptive manner. The literature includes examples of poor design for manufacturing and warnings of the obstacles to the implementation of concurrent engineering. There is no easy way to use the information to diagnose producibility problems in industry.

The framework assimilates a comprehensive range of principles, guidelines and case studies from literature, together with industrial producibility case examples into a practical tool that managers can use to specify particular actions to address their specific set of producibility problems.

1.7 Thesis Structure

This thesis is organised as follows:

Chapter 1 Introduction

1.1 Overview

1.2 Industrial Input to the Research

1.3 State of the Art

1.4 Research Objectives

1.5 Contribution to Knowledge

1.6 Research Methodology

1.7 Thesis Structure

Chapter 2 Research Methodology

The chapter describes the design of the research process and the reasons for the selection of the 'grounded theory' approach and associated methodology. The structure of the research is set out as 14 action steps. The implementation of each of the 14 steps is summarised.

Chapter 3 Industrial Rationale for the Research

This chapter describes how the producibility problem has evolved, through the work of the AEROEXTN project team on developing a template for CE in the extended enterprise and the author's subsequent studies of producibility interactions in civil aerospace.

The 'best practice' study undertaken at the start of the AEROEXTN project is reported, covering interviews with pairs of customers and manufacturing suppliers in a number of industries in addition to aerospace. The issues and enablers that resulted from workshops with the industrial collaborators were used to develop a template for the application of concurrent engineering in the extended enterprise. Live case studies were conducted for the AEROEXTN project and the civil aerospace studies, to gather data on concurrent engineering and design for manufacture. A list of practical producibility problems is presented.

Reflection on the shortcomings of the application of concurrent engineering and DFM principles led to the refinement of the research question.

Chapter 4 Literature Review

This chapter defines 'Producibility' and provides an overview of published literature on design, design models and methods, design for manufacture and concurrent engineering.

Designers' requirements for different levels of manufacturing information at various stages of the design process are set out. Sources of information that may provide or influence manufacturing information are outlined. These cover: training and experience; standards, reports, procedures and textbooks; CAD Systems, DFM tools and software; communications and teamworking.

Current approaches to Concurrent Engineering (CE) are addressed, and shortcomings of current methods are outlined. Material on human, social, communication and management subjects is included to provide guidance when considering the types of reasons for problems occurring in manufacturing.

The research gap addressed by this thesis is identified.

Chapter 5 Framework development

This chapter describes how producibility cases captured during the industrial research were combined with the literature study. The framework was developed to model the relationships between the reasons for manufacturing problems and the sources of information and influence.

Data from the early literature study and the case study research was used to help formulate concept categories and ideas for the types of reasons for problems in manufacturing and for the sources of producibility information. These categories were used to sensitise the author for the collection of further material from the literature, by showing the relevance of data from published case studies. A two-dimensional matrix was used to test relationships between the categories, using examples of producibility problems as factors. Several iterations were undertaken before the final framework format was frozen.

Examples are given of how the framework was populated to show the relationships.

Chapter 6 The Relationship Framework

This chapter presents the principal results of this research in the form of the final framework, consisting of a set of tables accompanied by notes, examples and references. These form an analysis of the relationship between the types of reasons for problems that occur in manufacturing and the sources of information and influence on design that may prevent them or help to optimise the process.

Chapter 7 Validation Illustrations

This chapter shows how the issues from the industrial case studies could be mapped to the relationship tables, and presents the industrial validity of the relationship framework.

Chapter 8 Discussion

This chapter discusses the significance of the work in the light of the state-of-the-art published material and industrial practice, and explains how the framework could be applied in an industrial situation to improve the design for manufacture process.

Chapter 9 Conclusion

This chapter describes the extent to which the Research Objectives have been met, sets out the justification for claiming an additional contribution to knowledge, and suggests ideas for future research.

Chapter 2 Methodology

This chapter describes how the methodology for this PhD research was derived and planned. Possible models of the research process are presented. The reasons for the selection of the grounded theory strategy and associated methodology are given.

The planned 14 action steps are presented, together with a detailed account of how each step was realised.

A clear distinction is drawn between the contribution made by the author towards the AEROEXTN project and the work done by him as an individual for this PhD research.

2.1 Models of the research process

Robson describes alternative models of the research process as follows:

- Positivistic, also known as natural-science based, hypothetico-deductive, quantitative or even simply 'scientific'. This calls for all data to be collected before starting to analyse it.
- Interpretive, also known as ethnographic or qualitative – among other labels. This has data collection and analysis intertwined.

The positivistic model involves five sequential stages:

1. Deducing a hypothesis from theory.
2. Expressing the hypothesis in operational terms that propose a relationship between two specific variables.
3. Testing the operational hypothesis by experiment or some other form of empirical inquiry.
4. Examining the outcome (to confirm or indicate the need for modifying the theory).
5. If necessary, modifying the theory in the light of the findings and repeating the cycle so as to verify the revised theory.

The interpretive model develops theories and concepts as the result of inquiry. They come after data collection rather than before it, hence this approach may be referred to as 'hypothesis generating' (rather than the 'hypothesis testing' of positivism). In the interpretive approach, data collection and analysis are not rigidly separated, but theories are formulated early and elaborated and checked as the process continues (Robson 1993) pp 18-19.

Glaser and Strauss describe 'Grounded Theory', a form of interpretive research commonly used within case studies. Theory is developed from the initial data gathered, and is then used to guide further data sampling (Glaser and Strauss 1967) p2 onwards.

Easterby-Smith et al view positivists as seeing the world as external with properties that should be measured objectively, independent of the observer's value and perception, while the interpretivists believe that reality is socially constructed and observation can never be free of the observer's values and experience. Table 2.1 summarises the key differences between the approaches (Easterby-Smith, Thorpe et al. 1991) p 27.

Table 2.1 Differences between positivistic and interpretive research methodologies

	Positivistic	Interpretive
Basic beliefs	World is external and objective Observer is independent Science is value-free	The world is socially constructed and subjective Observer is part of what is observed Science is driven by human interests
Research should:	Focus on facts Look for causality and fundamental laws Reduce phenomena to simplest elements Formulate hypotheses, then test them	Focus on meanings Try to understand what is happening Look at the totality of each situation Develop ideas through induction from data
Preferred methods include:	Operationalising concepts so that they can be measured Taking large samples	Using multiple methods to establish different views of phenomena Small samples investigated in-depth or over time

2.2 Methodology selection

The author was seeking a method to identify problems in manufacturing, and a means of relating them to the sources of information and influence that may prevent them reaching the shopfloor. It appeared that such problems and sources were not merely technical, but depended on human factors that were likely to be qualitative rather than quantitative. Because no established theories were evident, this research would need to build rather than test theory, for which purpose Gill and Johnson regard the interpretive route as being appropriate (Gill and Johnson 1991). It would be necessary to develop a framework and construct relationships, for which Adler regards the optimal research strategy as being inductive and qualitative rather than deductive and formal (Adler 1989) p 93.

One form of interpretive approach is the case study, which Robson describes as “a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence” (Robson 1993) p 5. Robert Yin regards a ‘case’ or ‘site’ as something to be studied in its own right, not as a sample from a population (Yin 1989). Denzin suggests that multiple and different sources (e.g. informants), methods, investigators or theories could be used to achieve ‘triangulation’ – as in surveying, where it is a means of finding out where something is by getting a ‘fix’ on it from two or more places (Denzin 1988). The use of such multiple methods has the important benefit of reducing inappropriate certainty, where a single line of investigation produces a clear-cut result that may lead investigators to believe they have found the ‘right’ or complete answer (Robson 1993) p 290.

The initial study of the literature had shown that a wide range of issues would be involved, and that many of these would be likely to have more than one possible cause or explanation. In order to identify these, a degree of probing was likely to be required to elicit details – especially where practitioners may be embarrassed that they had failed to anticipate problems. Considerable clarification may be needed where the different parties involved (e.g. Design and Manufacturing) do not agree as to exactly what happened or why. In such a situation, Daft and Lengel regard a rich communication channel such as the face-to-face interview as the appropriate mechanism to be effective (Daft and Lengel 1986).

In the absence of a theoretical framework for the analysis of the qualitative data gathered, Robson suggests an intermediate stage to assist in identifying themes that can form the basis for a workable descriptive framework (Robson 1993) p 378. In the real world of a complex case study, Yin recommends postulating simple patterns, such that a match is more likely to be seen at a gross level by 'eyeballing' the data. Iterative pattern matching can then be used to build up an explanation of the phenomena gathered (Yin 1989) pp 114-115.

The above considerations led to the selection of an interpretive approach for this research.

2.3 Grounded Theory

Glaser and Strauss describe 'Grounded Theory' as a strategy for qualitative research whereby the theory is derived from data and then illustrated by characteristic examples of data. The theory is therefore 'grounded' in the data, in contrast with logico-deductive theory. They warn that the logico-deductive notion of independence too often ends up being taken as a licence to generate theory from any source: happenstance, fantasy, and dream life, commonsense or conjecture, and then dress it up as a piece of logical deduction. They suggest that grounded theory is likely to be a better theory to the degree to which it has been inductively developed from social research. This does not prevent certain ideas, or even 'models' coming from sources other than the data e.g. flashes of insight, but the generating of theory from such insights must then be brought into relation to the data – or theory and the empirical world would mismatch (Glaser and Strauss 1967) pp 5-6.

Whereas verifying is the researcher's principal and vital task for existing theories, the main goal in developing new theories is their purposeful systematic generation from the data – verifying as much as possible is requisite while one discovers and generates the theory, but not to the point where verification becomes so paramount as to curb generation. Thus, generation of theory from comparative analysis both subsumes and assumes verification and accurate descriptions but only to the extent that the latter are in the service of generation. Otherwise they are sure to stifle it. The job is to develop a theory that accounts for much of the relevant behaviour, not to provide a perfect description of the area. The kind of evidence, as well as the number of cases, is not so crucial – a single case can indicate a general conceptual category or property (Glaser and Strauss 1967) pp 28-30.

An effective strategy recommended by Glaser and Strauss is, at first, to ignore the literature of theory and fact on the area under study, in order to ensure that the emergence of categories will not be contaminated by concepts more suited to different areas. Similarities and convergences with the literature can be established after the analytic core of categories has emerged. The type of concept that should be generated has two joint, essential, features. First, the concepts should be analytic and sufficiently generalised to designate characteristics of concrete entity, not the entities themselves. They should also be sensitizing – yield a 'meaningful' picture, abetted by apt illustrations that enable one to grasp the reference in terms of one's own experience (Glaser and Strauss 1967) pp 37-39.

2.4 Slices of data

Different kinds of data offer the analyst different views or vantage points from which to understand a category and to develop its properties: Glaser and Strauss called these 'slices of data'. While there are no limits to the techniques of data collection, the way they are used, or the types of data required, the practical constraint on the collection techniques that can best obtain the desired information is structural – e.g. who is available to be observed, talked with, interviewed, and at what times. The best data to obtain may include the trivial and anecdotal – only they must be theoretically relevant. Anecdotal comparison, through the researchers' own experiences, general knowledge or reading, and the stories of others, can offer useful comparisons especially when starting research in developing core categories. Researchers can then think where else they learned about the category and can make quick comparisons to start to develop it and sensitize themseves to its relevancies (Glaser and Strauss 1967) pp 65-66.

Stacey et al argue that narrative knowledge can be particularly valuable when researching very complex human dynamics. Narrative knowledge is embedded in anecdotes and stories, as well as the evaluation of those stories. The point is not whether they can be empirically validated or not, but whether they resonate with the experience of others and help them make sense of that experience (Stacey, Griffin et al. 2000) p 203.

The criterion for judging when to stop sampling the different groups relevant to a category is the category's 'theoretical saturation' – this means that no additional data are being found whereby the properties of the category can be developed further (Glaser and Strauss 1967) p 61. Miles and Huberman referred to saturation as occurring when there are "no significantly new explanations for this data". They point out that, if an analyst has collected his own data, then from time to time he will remember other incidents that he heard but did not record. If the unrecorded incident applies to an established category, either it can be ignored because the category is saturated, or (if it indicates a new property of the category) it can be added to this and then integrated into the theory. If the unrecorded incident generates a new category, both incident and category can be added toward their place in the theory – this may be enough if the matter is minor, but if it becomes central to the theory there is reason to return to the field or the library to collect more data (Miles and Huberman 1984) p 71.

2.5 Unit of analysis

The core subject around which the research is focused sets the boundary for data collection, and is determined by the research question. Yin differentiates between two versions of the single case study on the basis of the level of the unit of analysis. A study where the concern remains at a single, a global level is referred to as 'holistic'. This would apply to the study of an institution as a whole, the different functioning of separate sub-units within the institution (Yin 1989) p 17.

A holistic approach was appropriate to ensure that the research would include all aspects of the chain from design to manufacture. This meant that industrial collaborators would be asked for access to representatives of all appropriate functions, both internal and (where manufacturing was outsourced) external. The unit of analysis adopted was the 'producibility issue'. Each of these identified a DFM problem or query

2.6 Analytical framework

Some form of analytic framework was needed to relate the qualitative data collected to the concepts in the categories generated in accordance with the grounded theory outlined in Section 2.3 above. Miles and Huberman suggested how matrix displays may be used for such a purpose (Miles and Huberman 1984) pp 211-214. This approach was supported by Robson (Robson 1993) pp 390-393. A set of two-dimensional matrices was adopted as a framework for analysis. This allowed initial relationships between concepts to be displayed, and also sensitized the author to explore the possibility of additional relationships when gathering further data.

An electronic database was found to be extremely helpful as a method of storing notes on references and other material in a way that could be searched for keywords. Notes from many references, especially textbooks, covered a variety of relevant subjects that could be picked out in this way to support discussion in the appropriate area.

2.7 Validation

Table 2.2 Research validities and ways to achieve them

RECOMMENDED TESTS		RESEARCH STRATEGY	
Criterion	**Interpretivist viewpoint**	**Case study tactic**	**Phase of research**
Construct validity	Has the researcher gained full access to the knowledge and meanings of informants?	Triangulation by data source and by method to establish chain of evidence. Live case studies reviewed at on-site meetings with all functions represented, to achieve consensus or identify conflicting views. Variety of literature.	Data collection
Internal validity/ Reliability	Will different researchers make similar observations on different occasions?	Explanation building, but categories and relationships involved a degree of subjective interpretation. Illustrations of applications.	Data analysis
External validity/ Generalis-ability	How likely is it that ideas and theories generated in one setting will also apply in other settings?	Case study companies chosen from two different industry sectors. 'Best practice' broader. Much literature was general.	Research design

Easterby-Smith et al recommend three tests for case study research to ensure reliability and validity. These tests and the methods used in this research to achieve them are set out in Table 2.2 (after (Easterby-Smith, Thorpe et al. 1991) p 41, and (Yin 1989) p 41).

Table 2.3 Practical relevance of this research

Criterion	Question addressed	Demonstrated by this research:
Descriptive relevance	Does the research capture a 'real' problem for the 'practitioner'?	Discussions with practitioners in industry and feedback at seminars and conferences.
Goal relevance	Is the output of the research related to the objective/function of organisations?	Much literature is devoted to the development of management techniques such as concurrent engineering that improves efficiency, reduces time to market and cost, encourages innovation and inspires participants.
Timeliness	Do the phenomena change faster than science can come to grips with the problem?	Despite rapid changes in technology, most of the problems are related to the human, cultural and organisational aspects that require good leadership and management to prevent them.
Operational validity	Can the results of the research be implemented by manipulating causal variables?	The whole thrust of this research has been to present the results so as to draw attention to the causal variables, with the intention that this should help practitioners and researchers to address them.
Non-obviousness	Does the research simply reinvent the wheel?	While many of the issues appear obvious to those practitioners involved, and much is drawn from published literature, they are put together and presented in such a manner as to provide a new insight into the relationships between the types of problem and the influences on them.

Thomas and Tymon suggest that to ensure the practical relevance of management research it should meet five other criteria: descriptive relevance; goal relevance; timeliness; operational validity and non-obviousness (Thomas and Tymon 1982).

Table 2.3 summarises how this research demonstrates that these criteria for practical relevance were met.

Multiple and different sources were used to achieve 'triangulation', as discussed in Section 2.2 above, to avoid the results being too heavily dependent on a single industrial project or the views of particular individuals. Data were always sought from practitioners from design and manufacturing, as well as other functions involved in the design-to-manufacture chain, in order to obtain a balanced perspective. While the detailed live case studies were in the aerospace industry, the best practice interviews and literature covered a broader range of industries. Whenever a site visit was made, the author arranged for a tour of the shopfloor to observe processes at first hand, and where appropriate to talk to operators and supervisors as well as managers and executives.

2.8 Research steps

In the process of exploring the important issues in applying DFM in industry, the research started with a quest to develop methods to achieve CE across the supply chain. As this work progressed, it was realised that the fundamental understanding to relate manufacturing problems to design decisions was not in place, and problems could occur despite the adoption of CE. The research was then re-focused to develop a framework to relate possible reasons for manufacturing problems with sources of information and influence that could have prevented the problems, to show why they were not used.

Applying the grounded theory strategy of Glaser and Strauss outlined earlier, the following 14 action steps were adopted for this research:

Initial slice of data – gathered to support the initial research direction to plan for CE in the Extended Enterprise:

(1) 'Best Practice' studies;

(2) Literature review;

(3) CE implementation review;

Second slice of data – obtained from planning CE and analysing case studies:

(4) 'TO-BE' Task list;

(5) CE Template plus Initial Producibility Interaction model;

(6) SESAME pilot project: Monitor interactions and refine PI model;

(7) Analyse Producibility Interactions;

(8) Civil Aerospace studies;

Research refocused to look at why problems in manufacturing still exist, even with CE:

(9) Initial types of **reasons** for manufacturing problems;

(10) Concept categories for **reasons**;

(11) Concept categories for **sources** of information and influence;

(12) Framework to relate **reasons** to **sources**;

(13) Populate framework with factors and review;

(14) Validate framework through illustrations.

These steps are shown diagrammatically in Figure 2.1, and are explained in Section 2.9.

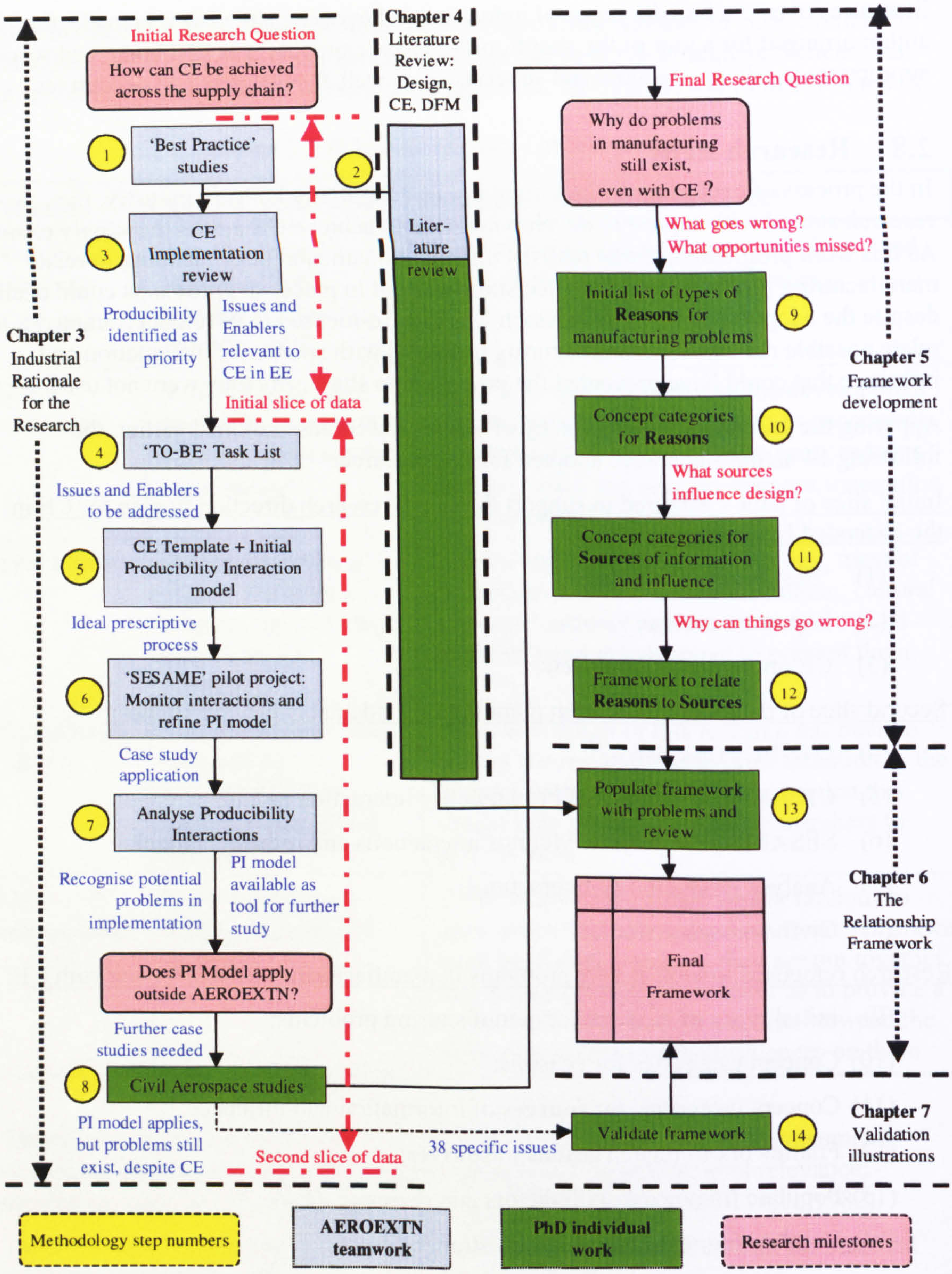

Figure 2.1: Methodology Steps

2.9 Research realisation

Figure 2.1 shows the relationship between research milestones and the 14 steps in the methodology, and distinguishes between the PhD work by the author as an individual and the work contributed as a member of the AEROEXTN project team. The diagram also indicates the Thesis chapters describing the work.

Details of the AEROEXTN project nature, structure and management are set out in Appendix B. Section B.1 defines the 'Supplier in the loop CE' (SIL-CE) approach for the project. Figure B.2 is a project flow chart showing where the work relates to the action steps of the PhD methodology.

The following sections describe the work done to complete each of the 14 steps.

2.9.1 Best practice study

In order to learn about current 'Best Practice' on SIL-CE in a range of industries that manufacture CAD-intensive custom parts, the author and the other full-time research assistant on the team looked at examples of how prime contractors worked with their suppliers. This was done at the start of the AEROEXTN Project, by conducting on-site semi-structured interviews of prime-supplier pairs. Prime-supplier pairs were selected to enable the extended enterprise to be viewed from both aspects, not just that of the prime.

The selection of companies for study drew upon the extensive range of contacts previously established by Research Managers and other members of the Department. Study cases covered a total of 12 prime-supplier pairs in the following industries:

- Military & civil Aerospace;
- Military & civil Telecommunications;
- Automotive and Retail electronics.

Although initiated with the principal purpose of looking at outsourced manufacturing, it was recognised that many of the considerations applied equally to the in-house manufacture and supply of parts. Appendix A provides a summary that compares the findings from different industries. Points from the study are covered in Chapter 3, Section 3.2.3.

During the best practice study, the researchers also made visits to the industrial collaborators sites so that they understood the current way of working (the 'AS-IS' scenario).

2.9.2 Literature review

Concurrently with the best practice study, published literature was studied to determine the state-of-the-art information up on how CE could be achieved across the supply chain. Subjects included Design, CE, DFM, outsourcing, communications and project management. Coverage consisted primarily of textbooks, journal articles, conference papers and trade magazines, with electronic databases used to search for relevant material using appropriate keywords. The author's role in the AEROEXTN research team included a principal responsibility for the subject of Producibility.

The focus of the research later changed to examining why problems in manufacturing still existed, even with CE. The author then made further extensive studies of the literature, and broadened the search to include subjects such as human error, culture and organisational matters. The literature review was mainly written *after* the data analysis has been completed, as recommended by Silverman, so that it could include critical comment and show how the work for this thesis fitted in with what had gone before (Silverman 2000) p 231.

2.9.3 CE implementation review

The first of two one-day workshops was held four months into the AEROEXTN project and the second four weeks later. The purpose of these workshops was to determine what actions were needed to set up SIL-CE between the principal industrial collaborators and ensure that their requirements and expectations were met. Experienced industrial managers attended, to represent both the customer and the supplier. Each workshop was structured as a whole-day session for the members of the academic team to present the results of the best practice and literature studies, and then to discuss the issues and enablers.

The output of these workshops was a prioritised list of issues and enablers to be used as an input to the 'TO-BE' task list. 'Producibility' was identified as the highest priority.

2.9.4 'TO-BE' task list

The next step was to determine what tasks would have to be completed in order to achieve the desired outcome. This was done by first comparing the issues and enablers that would represent the ideal 'TO-BE' scenario with the 'AS-IS' current processes, so as to identify the gap between them. The AEROEXTN team then addressed the potential weaknesses and problem areas so revealed, in order to compile a list of 'TO-BE' tasks that would be needed to prevent them.

2.9.5 CE template & initial PI model

The team developed the list of TO-BE tasks into an 'ideal' model of the SIL-CE process for the pilot project. This process was set out as a prescriptive CE template (Appendix B, Figure B.3), with producibility activities at the heart of it. The concept was to create the conditions for the design intent and the manufacturing implications to be thoroughly understood by all involved, encouraging a free exchange of views. This was so that potential problems and opportunities for improvement could be raised early enough for solutions to be developed at minimum cost.

The author became responsible for developing a 'Producibility Interaction' (PI) model in order to promote timely discussion during the pilot, and to ensure that no aspect of producibility was missed out. An initial list of subjects relevant to Producibility was compiled from the issues identified at the initial AEROEXTN workshops. This was then presented to a working group from the AEROEXTN team, including the appropriate customer and supplier function of specialists, especially Design and Manufacturing. The PI working group then ratified and expanded the subjects, and agreed on how they might best be addressed.

2.9.6 SESAME pilot project

The CE template was used to plan and manage SESAME. This was the code name for the live project to pilot the CE process for the design and manufacture of a small batch of missile parts. An integrated development team (IDT) was formed to progress the project, monitor the producibility interactions, and refine the PI model. The IDT held six meetings at monthly intervals over the period of the pilot.

2.9.7 Analyse producibility interactions

The detailed Case Study presented by SESAME enable the AEROEXTN team to capture the DFM changes made and the reasons for them. The effects were measured in terms of direct savings in set-up and machining man-hours, and the reduction in queries and late design changes. The results were evaluated against the cost of SIL-CE participation, and showed good cost benefits.

2.9.8 Civil aerospace studies

The success of the PI model in the AEROEXTN context of a small pilot project in defence aerospace led to the question of whether it would be relevant to a different sector of industry. Contacts in civil aerospace were approached to enable the author to undertake two further case studies, to use the PI model as a tool to review the Producibility of parts currently being manufactured. To broaden the field of application, diversity was sought in two ways: in-house and outsourced manufacture, and parts made from different materials. Both conditions were achieved, because the first Case Study involved a light alloy part machined in-house, while the second covered two sets of outsourced parts, one machined from titanium forgings and the other moulded from composites.

The author collected the data by interviewing separately representatives of the functions responsible for the design-to-manufacture chain for each of the parts, analysing the Producibility Interactions in a manner similar to SESAME, and reviewing the results against the PI model at on-site meetings with the representatives for each case.

With minor changes to the wording to reflect the broader range of production processes, the subjects in the PI model were found to cover the civil aerospace cases. However, problems in manufacturing still existed, even with the application of CE. The author therefore refocused the research question to ask why this should be so.

2.9.9 Initial list of types of reasons

The author reflected on the experiences of AEROEXTN and the civil aerospace studies, and considered that prescriptive use of the PI model depended for its success on the effectiveness with which the subjects were discussed and driven to a satisfactory resolution. This appeared to be more a matter of whether management encouraged and pursued the issues and enablers in the CE template so as to get the right people to discuss and act on Producibility at the right time, rather than whether people knew the PI subjects.

Acting on these considerations, the author drew ideas from the experience of the case studies and the continuing literature review to formulate a list of 35 types of reasons for problems that were likely answers to the following two questions on the Producibility process:

- What can go wrong?
- What opportunities could be missed?

2.9.10 Concept categories for reasons

To explore the problem space further, the 35 types of reasons were grouped into four categories. As suggested by Glaser and Strauss (see Section 2.4), this enabled the author to think where else he learned about each category so as to develop it and sensitize himself to its relevancies. Further refinement added a fifth category.

2.9.11 Concept categories for sources

Again reflecting upon the research experience, the author considered the ways in which designers may obtain producibility information or be influenced in their formulation of the manufacturing instructions. Ideas for sources were generated and grouped into five sensitizing categories to answer the question:

- What sources influenced design?

2.9.12 Framework structure

In order to relate the categories of reasons to the categories of sources, a two-dimensional matrix as suggested by Miles and Huberman (see Section 2.6) was adopted, with the types of reasons forming the rows and the source concept categories forming the columns. Each cell could then be used to relate a type of reason to a source by entering one or more factors in answer to the question:

- Why can things go wrong?

As well as issues that might cause difficulties in manufacturing, these factors included the potential causes of missed opportunities for improvement.

2.9.13 Populate framework

Once the outline framework had been set up, brief notes were entered in cells to show the sort of factor that might indicate a relationship, with footnotes added for explanation, examples and references from the literature, the AEROEXTN pilot project, the civil aerospace studies and the best practice study. Within each category of types of reasons, further rows and a fifth category were added to develop the framework, as one idea led to another. Several iterations were made, as suggested by Robson's 'playing with the data' to help identify themes (Robson 1993) p 378, before settling on a final arrangement.

The factors entered were checked for duplication and saturation, with the research notes being reviewed for additional examples and references to broaden the relationships. The framework was considered complete when no additional cells were filled, and further material served only to duplicate or reinforce the factors already entered without providing fresh insight into the nature of a relationship.

2.9.14 Validate framework

To check for framework completeness in respect of the SESAME and civil aerospace case studies, all 38 issues that had been raised during the studies were mapped on to the framework to verify that there was at least one factor in the framework to which each issue could be related.

The framework was reviewed to demonstrate that the validation criteria for practical relevance set out in Section 2.7 Table 2.3 were met.

2.10 Output of the research

The Relationship Framework represents the output of this research as a final set of tables relating the types of factors to the sources of information and influence. This is illustrated by examples and references to the literature and to industrial experience, to explain why manufacturing problems reach the shopfloor when sources of information are available to prevent them.

Chapter 3 Industrial Rationale for Research

This chapter explains how the research problem evolved during the investigation of the industrial problem, covering steps 1 to 8 of the methodology set out in Chapter 2. Details of the literature studied are covered separately in Chapter 4.

The initial research question "How can CE be achieved across the supply chain?" posed for the AEROEXTN Project described in Section 1.2 led to the recognition of Producibility as the priority subject, the development and application of a Producibility Interaction model, and the realisation that problems in manufacturing will still exist even with CE.

The initial slice of data (obtained from methodology steps 1 to 3) was the raw material gathered to find out what issues and enablers needed to be addressed in the live pilot project. Three elements contributed to this: a 'best practice' study over a range of industries; an initial review of the relevant literature; and a CE implementation review involving workshop discussions with the industrial collaborators to capture their concerns and priorities so as to arrive at a task list.

The second slice of data (obtained from methodology steps 4 to 8) was needed to find out the producibility issues that were raised in practice in the design-to-manufacture chain. This involved further workshops to arrive at a TO-BE task list and to formulate a Producibility Interaction (PI) model. This was the principal element of the CE template developed for the 'SESAME' live pilot phase of AEROEXTN. Thirteen producibility issues were raised and discussed during SESAME, and the PI model was refined. To determine whether the PI model could be applied outside the military aerospace context of AEROEXTN, the author carried out further case studies in civil aerospace, yielding a further 25 issues.

Although all the 38 issues raised were primarily technical in nature, it became clear that 'soft' influences permitted manufacturing problems to exist despite the application of CE. The final research question was then framed to focus on why this should be so.

3.1 The industrial context

The AEROEXTN project had been set up to develop concurrent engineering practices in the extended enterprise in the aerospace industry. Public funding had been made available to support this initiative because, although the aerospace sector had already achieved a degree of maturity in CE for the internal development of products, there was limited involvement of suppliers in CE. The increasing use of outsourcing for the manufacture of parts meant that the benefits of CE would be lost without the inclusion of suppliers. New drives for efficiency provided opportunities for restructuring of the supply chain.

This scenario provided a good opportunity to develop general DFM theory and, combined with Cranfield University's good contacts and close association with the aerospace industry, led to the choice of aerospace as the industrial context for this research.

3.2 The Best Practice Study

3.2.1 Scope

A 'Best Practice' study was conducted at the start of the AEROEXTN Project in order to investigate current CE practices in the extended enterprise. The term 'Best Practice' might more properly be called 'Good Practice', since there could have been better practices that the team did not find. However, the phrase was in vogue at the time and has been retained in this thesis.

The research team looked at examples of how prime contractors worked with their suppliers in a range of industries manufacturing CAD-intensive custom parts. Twelve prime-supplier pairs were selected to enable the extended enterprise to be viewed from both aspects, not just that of the prime. Study cases covered:

- Military & civil Aerospace;
- Military & civil Telecommunications;
- Automotive;
- Retail electronics.

3.2.2 Method

The study used on-site semi-structured interviews of industrial practitioners to cover the following topics: Product requirements; Engineering capability and skills; Design processes; IT Enablers: design/supplier interface; Supplier relationships; Intellectual Property Rights and Metrics.

3.2.3 Observations

A table summarising the results of the Best Practice study, as presented by the researchers to the first AEROEXTN one-day workshop, is at Appendix A. Each subject is represented in a table by a number of rows, one for each topic. The industrial firms visited were grouped as indicated in the column headings. One particular aircraft manufacturer and their suppliers had a particular way of working recorded under the heading 'Aircraft (1)', while observations from other aircraft manufacturers and their suppliers are shown under 'Aircraft (2)'. Although the study had looked at outsourced manufacturing, it was recognised that many of the considerations applied equally to the in-house manufacture and supply of parts.

Observations from the study were provided in this manner to stimulate discussion in the workshop sessions, and were very helpful in providing a basis for understanding the application of CE to a variety of industrial contexts. As a state-of-the-art assessment this formed a valuable anchor in reality. This acted as a counterpoint to the initial literature review, which tended to portray an optimistic view of what was possible with current technology rather than what was actually being achieved. For example, suppliers with a comprehensive 3D CAD capability were still required by some major customers to work with 2D paper drawings as the master contractual documents, although they exchanged data models electronically. In one case, the culture of the overseas customers had not yet allowed them to migrate to a fully electronic system, despite the existence for some years of the technical capability.

The best practice study made a significant contribution to the evolving research problem by demonstrating that awareness of CE practices and the availability of technology did not guarantee that industry would adopt or use them, and that lack of funding for investment was not necessarily the problem. It was also noted that the CE process needed to be tailored to the context in which the design-to-manufacture chain was operating.

3.2.4 CE implementation review workshops

The AEROEXTN workshops served two purposes. First, they acted as a means of capturing the in-depth industrial experience of the industrial collaborators, providing multiple disciplines and viewpoints, and ensured that the interpretation of the best practice study and the literature could be related to the real-world requirements of the target industry. Second, they helped to engender a common sense of purpose, commitment, and understanding of the contributions necessary to achieve success.

In order to obtain a balanced contribution from the industrial collaborators, with an appropriate level of expertise, the customer and the supplier were each represented by two mid-level managers. The sessions were co-chaired by the two academic Principal Investigators, supported by the two full-time researchers, including the author. The workshops were held in a room with projection facilities, flip charts and a large wall for hanging posters.

The academic team presented the results of the best practice study on a display of posters that showed the contents of Appendix A. This stimulated the discussion of the many examples of issues, enablers and metrics shown, and provided points that were added to the discussion column (incorporated in Appendix A as the final column in each table).

The industrial collaborators provided inputs on the current customer-supplier way of working (the 'AS-IS' process model), together with their priorities for the issues to be addressed and the metrics and enablers to be adopted to achieve SIL-CE. Producibility was identified as the highest priority subject, and it was recognised that the interactions between Design, Manufacturing and others involved in the design-to-manufacture chain would be at the heart of the CE process to be developed for the project.

3.2.5 Conclusions from first slice of data

The material gathered and discussed at the workshops contributed many ideas that were later included in various forms in the framework that represents the output of this PhD. There was a noticeable contrast between the ideal design-to-manufacture processes put forward in the literature, which tended to be based on developing original designs, and the real-world practices and limitations found in the best practice study, where most design work was incremental rather than original.

3.3 'TO-BE' task list

Further workshops were held to address the requirements for implementing CE and planning the pilot project. These resulted in a TO BE task list and the recognition of the timeline for each task. Tasks were grouped according to whether they had a long lead time, needed to be completed before the pilot project, would be carried out during the pilot, or were to be completed after the pilot. The output of these considerations formed the basis of the CE template that was subsequently constructed.

3.4 Producibility Interaction (PI) model

One output of the AEROEXTN project was to bring together the appropriate specialists in the design-to-manufacture chain at the appropriate time to address producibility matters for a live pilot project, named 'SESAME'. Details of AEROEXTN and the CE template that was applied to SESAME are set out in Appendix B.

To get the most from the producibility dialogue, it was important that the participants were prompted to raise all relevant subjects in a manner likely to promote the timely recognition of problems and opportunities. The PI model was developed as a tool to optimise the effectiveness of the PI discussions by providing a structure for this dialogue. Based on the issues and enablers raised during the earlier workshops, the author compiled an initial list of 24 subjects for consideration by a PI working group with the industrial collaborators.

The initial list of subjects relevant to Producibility was entered into a table with a row for each subject and columns headed to help structure the discussion. This initial model was presented to the PI working group, and refined at successive workshops as the project progressed. Each subject was addressed in turn, to assess who should raise it, its likely format, how it should be communicated, and remarks were added where necessary to focus on likely problems. The subjects that could be related to an initial CAD model of the part to be manufactured were indicated and grouped together. During the preparation for SESAME the subjects were developed from the initial 24 into a total of 29. These provided a comprehensive list of the topics that should be addressed to ensure a common understanding of design intent and production constraints, in the form shown in outline in Table 3.1. The PI table was subsequently used as a tool during the civil aerospace studies described in Section 3.7. A fuller version with remarks is set out in Appendix C.

Table 3.1 Producibility Interaction Table - Outline

Serial	Subject	Generated by			Format	Method of Comm'n	Remarks
		Des	Mfg	Other			
1	Concept/problem at hand	✔	✔	✔			
2	Change since last review	✔	✔				
3	Programme plan: cost/timescale/no req'd/milestones			Project Planners through Procurement			
4	Risk Assessment- Design	✔					

5	Risk Assessment- Production			✓				
6	Initial CAD model	Status & date	✓					
7		Physical Interface Definition	✓		Inputs from stress, aerodynamics			
8		Material properties	✓	✓				
9		Tolerances- key	✓		Input from Assembler needed			
10		Tolerances- manufacturing		✓				
11		Datum/clamping	✓	✓				
12		NC programming ease		✓				
13		Manufacturing limits: Capability (processes)		✓				
14		Manufacturing limits: Capacity (size)		✓				
15		Manufacturing limits: Capacity (throughput)		✓				
16		Special processes	✓					
17		Standards acceptability		✓				
18	Key Features-Design 2-D drawings-req't for format & views		✓					
19	Key Features-Production			✓				
20	Model req'ts-Designer		✓					
21	Test piece req't		✓	✓				
22	Process Plan			✓				
23	Jigs & fixtures			✓				
24	No. of separate set-ups and manufacturing activities, manufacturing time and specialist cutting tools			✓				
25	Integrated Development Team		✓					
26	Inspection Requirements				Quality			
27	Quality: Requirements for Manuf to Release				Supplier QA			
28	Quality: Requirements for Assembly to Accept				Prime QA/ Procurement			
29	Non-conforming parts				QA			

This PI model formed the centrepiece of the CE template that defined the 'ideal' prescriptive process that was applied to the SESAME pilot project.

3.5 SESAME Producibility Interactions

Full details of the SESAME pilot project are set out in Appendix B. Sections B.4.1 to 4.3 cover the industrial circumstances and membership of the integrated development team, together with the meeting and monitoring arrangements.

The monthly team meetings discussed project strategy and progress, reviewed the producibility issues raised, and helped to refine the PI model. Meanwhile, Design, Production and other specialists were free to exchange data and to discuss producibility issues outside the meetings, so that the design-to-manufacture process was not delayed. All such exchange activities were captured in separate log books by the designer and the production engineer.

Three formal iterations of the design CAD model and associated data were made over a period of six months. This reflected the fact that neither the Designers nor the Production Engineers were dedicated only to SESAME, and gave the research team a good opportunity to review progress at each stage.

A total of 13 technical issues were raised during the Producibility Interactions. These are tabulated in Appendix B Table B.1, together with the team's assessment of their importance, method of communication and impact.

It was observed that the PI Table served its purpose by encouraging the dialogue on the full range of subjects. It helped people to contribute their ideas, especially if they were junior or new to the project, when the Table called for them to take the lead on their specialist subject. Agreement on the format and method of communication of each subject helped people to get used to the idea of direct contact between team members, by telephone, fax, exchanging PC-viewable CAD model data, and (where available) e-mail. Communication and teamworking was also encouraged by the rotation of meeting locations, so that participants were able to show the others round their home site, and social activities such as regular team dinners.

3.5.1 Refinements to PI model

The PI table described in Section 3.3.1 had been used at each monthly team meeting during SESAME as a tool to prompt discussion and ensure that all subjects were covered. The sequence and content had been continually refined. Two examples of changes were:

- The subjects of Risk Assessments (Serials 4 and 5) and Quality/QA matters (Serials 27 to 29) in Table B.1 had been added at an early stage. Machine Capability was expanded from a single item to cover the three aspects of Capability (processes), Capacity (size) and Capacity (throughput) (Serials 13 to 15). Most of the subsequent changes in content involved the addition of remarks of the kind included in Appendix B.
- The sequence was modified slightly to reflect what was seen as a natural order in which subjects would arise. In particular, 'Inspection Requirements' was moved from the Initial CAD Model set (Serials 6 to 17) to later (Serial 26) on the advice of the Quality Manager, who considered that the final CAD model or drawings would be needed for a useful input.

The structure of the table was found to be broadly satisfactory. Appendix C shows an additional column that was included to relate the 13 SESAME issues and the 25 issues from the civil aerospace studies (see Section 3.7) to the appropriate subject or subjects under which they were raised.

3.6 Analysis of SESAME interactions

3.6.1 Cost benefits to companies

The impact assessments set out in Appendix B Section B4.4 were important aspects of the AEROEXTN Project. They were fed into the cost-effectiveness calculations for SESAME to produce the hard figures that demonstrated the significant savings in downstream costs that could be made by early supplier involvement in CE. Significant costs were avoided by preventing later changes. As the industrial collaborator remarked with regard to post-design queries and changes: "It costs £1000 to open the filing cabinet and look at the drawings, before any charges for further work."

These findings served to show that the SESAME dialogue could be guided successfully to avoid downstream problems. However, outside such a controlled pilot there was no certainty that the dialogue would take place. This concern, reinforced by the subsequent experience of the civil aerospace studies described in Chapter 3 Section 3.7 and Appendix D, led the author to consider what could go wrong and what opportunities might be missed.

In SESAME, all of the inputs on the part of the supplier were considered general recommendations, and were not specific to the supplier's machine capability. The civil aerospace studies subsequently showed examples of requests from the supplier for design changes to favour a particular production process.

The small number of 'critical' issues reflects the experience of the Senior Designer and the design not being a radical departure from previous work.

Most of the producibility issues shown in Table B.1 are easements. In a conventional make-to-print scenario the production engineer would probably have said: "Yes, we can make this", without feeling impelled to raise a formal suggestion for a change to ease manufacture. Three issues (3, 8 and 12) related to the provision of a tooling hole. First, the tooling hole was requested as a reference for manufacture. This was readily agreed, and its size and position were discussed. Then, when it appeared on the Key Features Drawing (KFD), the Production Engineers could see that a tight tolerance had been placed on it: a precise location was not needed for it to serve its purpose. Either additional production time would be needed to ensure the tolerance was met, or else the part might be rejected at inspection. In contrast to some of the other easements, a simple set of producibility guidelines would not have led the designer to provide the optimum tooling hole for a part of such complex geometry; these three issues demonstrated the benefit of the direct dialogue between Design and Production.

There was only one issue of redundant design effort, but this illustrated two things. First, the designer's approach was 'DFM-orientated', in that he knew that the way the model was constructed could affect manufacture. Second, he felt able to discuss the subject freely in the team forum, without attempting to hide behind the 'mystery' of Design.

Of the 13 points raised, 11 were accepted by Design. One was not technically acceptable. The remaining issue resulted in the designer adopting a different easement from that proposed by the supplier, because the original suggestion could not meet the stress analysis requirements. SESAME did not produce any requests for easements that would have achieved the reduction of the manufacturing cost but compromised a performance parameter such as weight, requiring a 'trade-off' discussion of the kind later found in civil aerospace.

3.6.2 Communications

While only two issues are listed under the 'personal contact' heading, this does not fully reflect the importance of personal contact in establishing the team atmosphere of co-operation and trust that encouraged the full use of the model and drawing information. Team membership promoted a sense of co-operation, with everyone willing to participate and contribute to the common purpose.

A low-cost model viewer was very successful in allowing early sight of the design without the difficulty and expense of operating a full CAD workstation. Because the supplier was not sub-contracted to carry out any design work, there was no requirement to set up a high-capacity link for the rapid transfer of large CAD files. The nature of the defence work was such that suppliers would not have been given access to the full CAD files with assembly information. Instead of this, the designer was able to use the main CAD system to generate IGES or STL files for the low-cost viewer. The Production Engineers found that they could rapidly learn to manipulate this model on a PC, examine the features and interrogate approximate dimensions (these were accurate enough for producibility assessment, but would not have been adequate for Quality to use for inspection purposes on the finished part). Because it was easy to view sections of the model and look at it from all aspects, both internal and external, one Producibility Engineer exclaimed that it was "better than having a solid model, or even the real part!"

Some aspects of the design could not readily be conveyed on the model, and were the subject of supplementary drawings, data sheets or standards. Because of the wish to involve the supplier as soon as the early design was available, no drawing was produced until the second iteration of the model. Discussion of the completeness of the information conveyed by the model led to the response that certain aspects would be defined on the KFD. There was no doubt that early communication with the supplier enabled Design to develop a package of information that helped the supplier to understand what was required as well as incorporating the supplier's suggestions for ease of manufacture. Many such suggestions would not have resulted from Design applying a standard DFM software package. In some instances, Design would have had to carry out a lot of work using a DFM package to evaluate alternative approaches, whereas the Production Engineer could make a rapid assessment and advise Design of the need for changes only when these would have a significant impact on production.

The dialogue also stimulated requests for information that the CAD system made readily available to Design, such as the surface area for plating purposes, which traditionally had been worked out by the plating shop from the drawings.

There were two other aspects that are not represented in Table B.1, as a result of the discussions during the development of the PI Table. The first was the realisation by the customer that their tolerance standards, based on a document some 30 years old, were in urgent need of review. The second was the offer of an alternative material that would work out cheaper for the small quantities needed than the material originally specified, which had a minimum order quantity of 100 kg. The offered material was actually to a higher aerospace specification, but was already used extensively for other work by the supplier. However, the designer would not have specified it from the catalogue without prompting from local knowledge.

3.6.3 SESAME conclusions

The overall conclusion drawn from SESAME by the AEROEXTN project team was that well-managed CE in the Extended Enterprise gave good results, benefiting both customer and supplier. The improved understanding of design intent was more significant than the direct savings in estimated set-up and machining times, because this was likely to result in the elimination of most, if not all, design queries and engineering changes.

Much was learnt about the management, organisational, and cultural aspects necessary for the technical dialogue to take place effectively. Some of the explicit lessons learned from setting up a concurrent engineering project of this nature in the extended enterprise are set out in Appendix B Section B.4.5.

The author also gained a lot of tacit information about the way the design-to-manufacture chain worked in practice, which was very helpful in shaping his approach to the PhD work subsequent to AEROEXTN. For example, it was readily apparent how the pressures on designers to focus on their principal task of reaching a workable design solution meant that, once they had satisfied themselves that a part was manufacturable, they would not normally spend time considering the finer points of producibility. Also, it was very rewarding to see how the supplier's production engineers (long used to being on the receiving end of drawings subject to competitive tender) reacted positively when they recognised that they could have a dialogue with the designer.

The potential problems in implementation led the author to see whether the PI model could successfully be applied outside the context of the defence aerospace industry.

The need for further case studies prompted the author to approach two major civil aerospace contractors reported in the following Section 3.7.

3.7 Civil aerospace studies

3.7.1 Purpose of studies

The purpose of the civil aerospace studies was to investigate whether PI model would be applicable to the design-to-manufacture chain outside the limitations of the AEROEXTN/SESAME small pilot project in a defence aerospace context.

The civil aerospace sector was chosen to provide a different business environment from defence aerospace, while still requiring high value-added custom parts of a complexity that would justify producibility interactions. In addition, Cranfield University's close ties with the aerospace industry provided contacts willing to allow the author to conduct the research.

The aim was to study parts that were currently in production, and find out from the people directly involved what producibility interactions had already taken place, what problems had reached manufacturing, and whether the application of the AEROEXTN PI model could have been applied with advantage.

3.7.2 Case studies

The circumstances of the civil aerospace industrial case studies were as follows:

- The customer (Company A) was a major civil aircraft Original Equipment Manufacturer (OEM), who outsourced the manufacture of approximately 70 percent of parts, retaining design, assembly, systems integration and test;
- Company A maintained an in-house capability for machining;
- The supplier (Company B) undertook a wide variety of civil and military aerospace manufacturing tasks;
- The distance between OEM design and supplier manufacturing sites was some 180 miles by road;
- The nature of the product required complex CAD-designed mechanical machined and composite parts to enable the aircraft to carry its full payload for a given range and speed;
- The customer saw time-to-market as important in keeping to a demanding build schedule;
- The parts were required in low volume, to match an aircraft production rate of one set per month;
- Individual component cost was medium; however, design risk and potential project impact were high.

Three sets of aircraft parts were studied:

- **Part A** was manufactured in-house by Company A, milled from aluminium alloy plate in three stages by a five-axis high-speed machine.
- **Parts T** were manufactured by Company B, using four- and five-axis machines to mill and drill three types of part from titanium forgings;
- **Parts C** were manufactured by Company B, as a set of four types of composite panels. These were formed by placing epoxy-resin-impregnated layers of carbon fibre, aramid fibre (Kevlar), glass fibre and aluminium foil in a mould and curing them under heat and pressure in an autoclave.

3.7.3 Data collection

A week was spent on site for each of the two studies, full details of which are set out in Appendix C. In each case, an initial meeting with functional representatives was held for the author to explain the scope and purpose of the study. This was followed by semi-structured interviews with Manufacturing to identify manufacturing problems and other producibility matters relating to the selected parts. Visits were made to the manufacturing shopfloors, and also to the main structure assembly facility.

Report forms were raised to characterise each of the parts studied, as shown in Appendix D. Further interviews were conducted with Design, Quality and Procurement specialists who had been involved in the design-to-manufacture chain of the parts concerned.

Each study was completed with a review meeting attended by representatives of the specialist functions. The context of each project was discussed and consensus obtained on the nature of every issue. The Producibility Interaction Model was then reviewed, and the issues related to the subjects in the PI Table.

3.7.4 Issues & Analysis

The unit of analysis for the civil aerospace studies was the producibility issue, raised by any functional specialist, which required a response by Design for clarification or change. A total of 25 such issues were raised in total for the three sets of Parts A, T, and C, and are set out in Appendix D. Tables D.1, D.2 and D.3 summarise the issues, their importance, method of communication and impact in a similar manner to that used in Appendix B Table B.1 for AEROEXTN.

3.7.5 Civil aerospace studies conclusion

The civil aerospace studies served four purposes:

- They confirmed the benefits of producibility interactions in addressing manufacturing problems (e.g. three of the five issues raised during the in-house study of Part C were resolved at the review meeting, when the design specialist agreed to take action as a direct result of the discussion);
- They showed that real-world problems were not always addressed in a timely manner (e.g. the lack of feedback from the previous manufacturers to correct queries on the drawings for parts now being manufactured in-house; delays in starting the producibility dialogue while awaiting strategic decisions on sourcing);
- They showed that real design teams were not always able to conform to company standards for the design process. E.g. for relatively new technologies, such as composite panels, the lack of a Design Handbook and the shortage of a Design Leader at the early development stage were reported as having a significant influence in increasing the number of producibility matters to be resolved.
- They showed that the PI model developed for AEROEXTN was accepted as being both relevant and complete by the industrial practitioners, and could have been adopted as a tool to assist management to structure discussions between Design, Manufacturing and other relevant functions at an early stage in the development process.

3.8 Summary of live case study results

3.8.1 Characteristics of AEROEXTN and civil aerospace parts studied

Table 3.2 Characteristics of parts studied

Characteristics	SESAME	Part A	Parts T	Parts C
Aerospace sector	Defence	Civil	Civil	Civil
Project	Missile	Airliner	Airliner	Airliner
Supply	Outsourced	Internal	Outsourced	Outsourced
Material	Steel	Aluminium	Titanium	Composite
Part size (max dim)	< 300 mm	3.2 m	640 mm	1.5 m
Part classification	New	Change of manufacturer	Derivative	Derivative
Batch size	Small	Small	Small	Small
Manufacturing methods	Manually machined	5-axis machined from plate	4 & 5-axis machined forging	Pre-preg lay-up autoclave cured

Table 3.2 shows a summary of the characteristics of civil aerospace parts studied, compared with the SESAME parts in AEROEXTN. It should be noted that although there is diversity because each type of part is made from different materials and by different methods by different sets of people, and was designed by different teams, they were all made in small batches. It cannot therefore be assumed that all producibility matters common to these studies would necessarily apply to larger batches or mass-produced items.

3.8.2 Summary of issues raised

Table 3.3 summarises the importance, channel and impact of the issues raised in the producibility interactions of the four industrial case studies. Over half the issues raised were regarded as easements, but some 40% were classed as critical, i.e. manufacturing could not proceed without risk until the matter was resolved.

The single case of redundant design was unusual, but it did demonstrate the designer's awareness that the 3D modelling method could have affected manufacturing, and under different circumstances might have made a significant difference to the design workload.

Table 3.3 Importance, channel and impact of issues raised

Issues		AEROEXTN	Part A	Parts T	Parts C	**Total**
No of issues		13	5	7	13	38
Importance:	Critical to D/M	3	3	4	5	15
	Easements	9	2	3	8	21
	Redundant Design	1	0	0	0	1
Method of communication:	Personal contact	1	0	0	6	7
	Model view	9	4	5	2	20
	Drawing only	3	1	2	5	11
Impact:	Major change for Design	5	1	1	5	12
	Minor change for Design	6	4	6	8	24
	Major change for Manufacture	7	3	6	6	22
	Minor change for Manufacture	2	2	1	7	12

3.8.3 Summary of Producibility issues

The producibility issues raised in the studies so far covered both problems and opportunities for improvement, as follows:

Problems (What can go wrong?)

- Query on drawing/model: error/inconsistency; ambiguity/omission.
- Part is impossible to make with existing processes:
  - Outside capability limits (e.g. size, weight, tolerances, wall thickness, throughput...);
  - Inaccessible features.
- Part is difficult to make with existing processes:
  - Near limit of process capability (e.g. high scrap/rework rate);
  - Time-consuming setup;
  - Lack of datums/clamping;
  - Proliferation of features/complex geometry;
  - Poor access for machining heads;

  - Requires special cutting tools;
  - Requires complex tooling/jigs;
  - Materials are difficult to work;
  - Geometry liable to distort during processing;
  - Requires exceptionally skilled machine operator;
  - Difficult to inspect part for compliance with drawing/model.

What could be improved? (What opportunities are missed?)

- Presentation of information by drawings or models: clear; complete; ambiguous; error-free.
- Programme information combined with risk assessment could promote early trials, tests of capability and training of operators for developing and proving production processes to avoid surprises and enable early changes to modify design or process as necessary.
- Part is optimised for manufacture:
  - Well within process capability, with operators of average skill;
  - Features standardised (e.g. avoid use of different-sized fastener holes, non-standard fillet radii);
  - Shape uses raw material efficiently (e.g. relationship to stock sizes);
  - Material is easy to handle at all stages;
  - Geometry is improved for ease of manufacture (e.g. minimum number of set-ups, use of standard tools, minimum number of tools, easy access for tool heads);
  - Minimises environmental impact (energy consumption, noise, toxic chemicals, special safety procedures);
  - Tolerances are modified for ease of manufacture (e.g. reduced area or length where close tolerance required, without compromising function)
  - Takes advantage of local conditions/opportunities;
  - Inspection requirements are limited to critical features;
  - Production process proved, rather than part inspected.

3.9 Refining the Research Question

Following the initial review of the literature, the best practice study, the workshop discussions with industrial collaborators on the AEROEXTN Project and the experience from the civil aerospace study, the author considered where his PhD research could most usefully be directed. He pursued the idea that, if producibility were the subject of greatest concern for industry in the context of CE, despite all the design tools available, then it would be important to explore the reasons that might prevent designs from being optimised for manufacture.

The PI model prompted discussion between the relevant functions at the appropriate stage in development, on issues of the kind summarised in Section 3.8.3, but did not compel people to solve them in the optimum manner. In most cases the necessary information was known, or the need to generate it could have been recognised at an early stage. The focus of the research therefore became to find out why people do not use the information available to them. Two aspects in particular needed to be addressed:

1. What sources influence design?
2. Why don't people use the available information? - Why can things go wrong?

If it were assumed that:

Information that would enable the design of a part to be optimised for manufacture existed somewhere, or could be generated in some way, **and**

The design was not optimised for manufacture before manufacturing instructions were issued to the shopfloor for the part to be made.

Then:

Some influence or influences prevented the designer from receiving the information and acting upon it.

This led to the **final research question** for this thesis being identified as:

> **"Why do manufacturing problems reach the shopfloor when sources of information are available to prevent them?"**

Definitions:

Manufacturing	The making of individual parts
Manufacturing problems	Manufacturing information is missing, inconsistent or corrupt The parts are difficult or impossible to make Manufacturing could be done better
Reach the shopfloor	Manufacturing instructions reach those tasked or contracted to make the parts
Sources of information	Any means whereby information might be known or be generated. In Chapter 5 such sources are categorised as: • Training and experience • Standards, textbooks, reports, specifications and procedures • CAD Systems • Design for manufacture (DFM) tools and software • Communication and Teamworking
Available	The requisite information existed, or could have been generated, and a mechanism existed by which it could have been accessed during the design process
Prevent	Changes that could have been made in the design process to alter the manufacturing instructions before they were issued to the shopfloor

Chapter 4 Literature Review

In order to obtain an understanding of material relevant to the pursuit of the research question, this chapter starts with a review of literature on the principles of concurrent engineering (CE), producibility, the design process, and the manufacturing information requirements for designers.

The principal thrust of Sections 4.1 to 4.4 is to report on what writers on these subjects regard as the way to achieve a successful design-to-manufacture process.

Section 4.5 looks at the sources of producibility information to influence designers, including material on engineering, social, communication and management subjects.

Section 4.6 examines the shortcomings of current systems and considers the types of reasons for problems occurring in manufacturing, including material on human, social, communication and management subjects.

Finally, Section 4.7 considers the gap in research that this thesis is aimed at filling.

Use of literature

The references contained in this chapter were not all found at the start of the research. This follows Silverman's argument that a literature review should mainly be written *after* the data analysis has been completed (Silverman 2000) p 231. The basic principles were looked at early, but it was in the nature of 'grounded theory' qualitative research that the subjects to be explored should emerge as a result of the continuing compilation and analysis of data. Electronic databases were searched for relevant topics, and new material gathered, throughout the period of research.

In addition to the literature referred to in this chapter, there are many more detailed references that form part of framework tables and notes in Chapter 6 to illustrate specific examples of the relationships between types of problems in manufacturing and sources of information and influence to prevent them. To avoid duplication, such further references have been omitted from this chapter.

4.1 Concurrent Engineering (CE)

The concept of CE is important because of its increasing use to bring together the people involved in the design-to-manufacturing chain and to overlap their activities in time (i.e. concurrency) to bring about significant improvements in effectiveness.

R P Smith provides a useful history of the ideas and themes involved since the 19th-century, and shows how CE may be seen as a summary of best practice in product development, rather than the adoption of a radically new set of ideas. He suggests that the concurrent engineering ideas have existed for a long time, but were not put into practice both because older methods seemed easier and because the educational system did not advocate sufficiently a change to preexisting practices (Smith 1997) p76.

4.1.1 Concurrent Engineering Principles

The traditional attitude of designers had been 'we design it, you build it', now termed the 'over-the-wall approach'. This occurs where the designer is sitting on one side of the wall and throwing the designs over the wall to the manufacturing engineers who then have to deal with the various manufacturing problems arising because they were not involved in the design effort. The teamwork resulting from consulting the manufacturing engineers at the design stage is known as 'simultaneous' or 'concurrent' engineering. The benefits claimed include reduction in overall cost, reduction in time to market (from design concept to production delivery) and improvement in quality (Boothroyd, Dewhurst et al. 1994).

Cleetus traces the history from the first definition of the term 'concurrent engineering' given in a report by Winner et al to the United States Institute of Defense Analyses (Winner, Pennell et al. 1988):

> "Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements."

In 1992 the Concurrent Engineering Research Center (CERC), set up by the Defense Advanced Research Projects Agency (DARPA), put forward a new, more general definition:

> "Concurrent engineering is a systematic approach to integrated product development that emphasises response to customer expectations and embodies team values of co-operation, trust and sharing in such a manner that decision-making proceeds with large intervals of parallel working by all life-cycle perspectives early in the process, synchronised by comparatively brief exchanges to produce consensus."

Cleetus claimed that no single idea of CE was new in the late 1980s, but putting it all together resulted in new insights and inspiration for new approach. The uniqueness of CE lay not so much in fundamental insights as into their practical consequences (Cleetus 1998) pp 249-251.

Dimanescu and Dwenger also quote the 1988 study, regarding it as a sharp conceptual break with long-held management practices. The old-style hand-off from design to manufacture "It's your problem now" was no longer acceptable, but few companies had by then found a 'best way' of achieving concurrency in their development projects (Dimancescu and Dwenger 1996) p 44.

A number of textbooks cover concurrent engineering principles, e.g.: Pahl and Beitz 1984 and 1995; Pugh 1990 and 1996; Clark and Wheelwright 1995; Bralla 1986 and 1996; Niebel and Draper 1974; Prasad 1996 and 1997; and Todd 1995. These each include broadly similar advice on the principles of improving producibility by applying various rules, most of which would be familiar to experienced design and manufacturing engineers. Software programmes are available to assist in the assessment of design-for-assembly and design-for-manufacture quality by reducing the number of parts (especially fasteners), reducing set-up requirements, adjusting tolerances, etc. While many references are made to involving suppliers as appropriate, there are few rules put forward as to how this should be done in practice.

4.1.2 Implementation of CE

Kormos reports a few clear patterns that had begun to emerge from his experience of reviewing hundreds of CE and integrated product-development (IPD) programs, while judging award schemes over a number of years. He lists four key items for many companies to have a CE capability:

- Basic CAD and simulation tools, often in their second or third generation;
- Cross-functional teams;
- A formal and well-documented system for managing projects.
- A robust program for integrating engineering and manufacturing, generally through early design reviews and use of various Design-for-X methods.

It can take even a well-managed organisation years to get these four areas right. Others never seem to get there at all. Kormos regarded the vast majority of CE programs examined as having reached 'stage-two maturity', but somehow found it hard to progress further. They had defined cross-functional teams that brought some measure of improvement. Products come out more or less on schedule, but with spotty market success. There were fewer producibility issues and more consistency from project to project.

Kormos suggested a number of issues that characterised the product-development companies that had reached greater CE maturity. One focus was on methods for harvesting knowledge from completed projects to minimise 'wheel spinning'. Qualities common to this advanced form of IPD maturity included advanced collaboration. Exemplary programs generally invested in technology that fostered communication and information sharing among team members. The best firms were well beyond e-mail and shared project schedules. They collaborated electronically across physical and organisational boundaries (Kormos 1998).

4.1.3 Integrated product development teams

Weber describes how aerospace companies had been moving to form integrated product development teams in order to improve their new product introduction process. These teams consisted of specialists from a wide range of disciplines who could interact early in the design process to speed up the timescale and also to reduce the risk of later-life problems incurring cost. The mix of disciplines would shift and change over the life of the team. At the start, it would be primarily design with some representation from manufacturing, tooling and other disciplines. By the time full rate production commenced, the IPD teams would shift to a major emphasis on production and support disciplines, with design engineering, manufacturing and tooling disciplines staffed to handle the required product and process changes (Weber 1994).

Weber emphasises the importance of effective and sufficient horizontal communication between the IPD teams to avoid IPD 'silos'. The traditional 'silos' were the design engineers' silo, strength engineers' silo, tool designers' silo, manufacturing engineers' silo, etc: now IPD teams need to avoid the tendency to have IPD 'silos', each silo consisting of a design engineer, a strength engineer, a tool designer, a manufacturing engineer, etc. Where significant components were outsourced, the suppliers' expertise needed to be harnessed. People need persuading that the potential benefits outweigh the likely additional time and effort necessary to involve suppliers with Design. The problem was how to do this effectively in a manner that benefited both customer and supplier (the 'win-win' solution) (Weber 1994) p 22.

New and Burnes reported that the more an activity involved changes in both the customer's and the supplier's operations, the more there was likely to be an even distribution of costs and benefits. Similarly, the more an activity was focused on the supplier, the more likely it was that the supplier would pay the costs and the customer would reap the benefits (New and Burnes 1998).

In the context of better outsourcing, Quinn regarded the question as not just whether to make or buy, but how to evaluate and achieve the desired balance between the independence and efficiency incentives needed to stimulate a supplier and the buyer's needs for control and security (Quinn 1999) p 9.

> "A primary reason for outsourcing is to leverage the supplier's greater skills, knowledge bases, investments, and processes. If the buyer specifies how to do the job in detail, it will kill innovation and vitiate the supplier's real advantage. Time spent in early stages to investigate and ensure the congruence of the supplier's and buyer's value systems and incentive structures is invaluable.... Without goal congruence, control costs become excessive for both parties. With it, benefits multiply and costs plummet. With proper monitoring, companies repeatedly find that – instead of losing knowledge capabilities – the sum of outside suppliers' knowledge, the stimulation and insights they provide, and the solutions they develop will vastly exceed the potentials of any inside group, unless that group is the company's core competency. A most common error is to ignore the internal costs of non-innovation, missed opportunities, delays, management time expenditures, and inefficiencies due to internal suppliers' having an ensured customer. Some of the greatest values of outsourcing are the opportunistic ideas that the company otherwise would never see."

4.2 Producibility

The concept of **'producibility'** is fundamental to a consideration of problems that occur in manufacturing. Bralla defines this as being synonymous with **'manufacturability'** (Bralla 1996):

> "By manufacturability we mean the ease with which a product or component can be produced, its simplicity, the straightforwardness of its configuration, the degree to which it minimises labour, materials, and overhead costs, and the freedom that its design has from inherent quality and processing problems."

The major influence on producibility is that of design. Bralla asserts that:

- The most significant manufacturing-cost reductions and cost avoidances are those that result from changes to product design rather than from changes in manufacturing methods or systems (Bralla 1986) p XII;
- The most producible designs are provided when the designer and manufacturing personnel, particularly manufacturing engineers, work closely together from the outset. (Bralla 1986) p 1.

4.3 Design – Definition, Models and Methods

4.3.1 Definition of design

Hubka and Eder distinguish between two interpretations of the word 'design': as a *noun*, meaning the outward appearance and pattern of artificial objects, artefacts, systems and products, and as a *verb*, meaning the process of establishing which of several alternative ways (and with what tools) things could be done, which of these is most promising, and how to implement that choice, with continual reviews, additions and corrections to the work. The *process* interpretation is seen as more important in the context of engineering, although in some ways both object and activity must be co-ordinated (Hubka and Eder 1996) p ix.

Alexander presented an error-reduction perspective of design:

> "Every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem. In design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context. Good fit is the desired property of this ensemble which relates to some particular division of the ensemble into form and context" (Alexander 1964) pp 15-16.

The *process* interpretation was adopted in a survey carried out by Evbuomwan et al, who incorporated a number of definitions of 'design' in describing it as (Evbuomwan, Sivaloganathan et al. 1996) p 302:

> "The process of establishing requirements based on human needs, transforming them into performance specification and functions, which are then mapped and converted (subject to constraints) into Design solutions (using creativity, scientific principles and technical knowledge) that can be economically manufactured and produced."

It is significant that the more recent approaches emphasise the design process rather than the design object. Hammer and Champy now state in their latest edition that 'processes' is the most important word in their definition of reengineering, overtaking 'radical', which had been regarded as more important in 1993 (Hammer and Champy 2001) p 38.

4.3.2 Design process models

Evbuomwan distinguishes between prescriptive and descriptive design models arising from various philosophies or strategies in the past. The prescriptive models tend to look at the design process from a global perspective, covering the procedural steps, i.e. suggesting the best way something should be done. The descriptive models are concerned with designers' actions and activities during the design process, i.e. what is involved in designing and/or how it is done. More recently, a third group of computational models has been developed. These place emphasis on the use of numerical and qualitative computational techniques, artificial intelligence techniques, combined with modern computing technologies. These three classes of design models all share some common characteristics.

The majority of the **prescriptive models** on the design process are based on the procedural steps of the design activities (analysis, synthesis, evaluation, decisions, etc.), while others based their steps on what can be regarded as the phases/stages of design (conceptual design, embodiment design and detailed design). The models that were based on the phases of the design process include those of Asimow (1962), Pahl and Beitz (1984), Pugh (1990), VDI 2221 (transl. by Wallace 1987), Watts (1996), Wheelwright and Clark (1992), Hubka (1992) and French (1971). The models, except for those of French and VDI 2221, also contained in a more detailed form within each of the design phases/stages, the design activities that characterised a majority of the other models. The Watts model showed only the two ends of the design phase, i.e. abstract and concrete, with the interval between represented by a cyclic (iterative, refining and progressive) process.

The models that were based on design activities included those by Jones (Jones and Thornley 1962), Marples (1960 pp 1-16), Archer (1984), Krick (1969), Cross (1991) and Harris (1980). It can also be observed that in all of the models, three key activities were predominant, i.e. **analysis, synthesis** and **evaluation.** Analysis was mostly related to analysing the design problem, requirements and specifications. Synthesis was concerned with generating ideas, proposing solutions to large or small design problems as well as exploring the design solution space, while evaluation involved the appraisal of design solutions in order to establish whether they satisfied the requirements and specifications and set corporate criteria. The sequence in general also tended to be analysis first, followed by synthesis and evaluation. In the model by Krick, synthesis was replaced by search and evaluation by decision. The model by Harris represented analysis, synthesis and evaluation by appraisal of the task, conception and appraisal of concepts respectively.

It is not surprising that the three activities of analysis, synthesis and evaluation were predominant as they represent the core of the design process. If proper analysis of the problem or requirements is not carried out, synthesising solutions will be difficult and inappropriate solutions might be the result. Once plausible solutions are created, there is then the needed to evaluate, test and assess their fidelity to the originating requirements and specifications as well as set criteria.

Besides the three activities, there are, however, other necessary activities that should be performed during the design process, such as optimisation, revision, data collection, documentation, communication, selection, decision-making, modelling, etc. Some of these activities were included in some of the models.

4.3.3 Prescriptive models based on product attributes

Suh reasoned that the majority of product or systems failures could be attributed to any or a combination of the following:

- incorrect or excessive functional requirements;
- continuing alterations to functional requirements;
- wrong design decisions;
- the inability to recognise faulty decisions early enough to rectify them.

The existence of unacceptable designs as well as good designs suggested that there should be some features or attributes that could distinguish between good and unacceptable designs. This led to Suh's axiomatic approach to design based on attributes of the design produced (Suh 1988). The two fundamental axioms that can guide decisions to maximise the productivity of the total manufacturing system are:

- Axiom 1: In good design the independence of functional requirements is maintained.
- Axiom 2: Among the designs that satisfy Axiom 1 the best design is the one that has the minimum information content.

Some of the important design corollaries that follow from these axioms are:

- Decouple or separate parts or aspects of a solution if functional requirements are coupled or become coupled in the design of products and processes.
- Integrate functional requirements into a single Physical Part or solution if they can be independently satisfied in the proposed solution.
- Minimise the number of functional requirements and constraints.
- Use standardised or interchangeable parts whenever possible.
- Make use of symmetry to reduce the information content.
- Conserve materials and energy.
- A part should be a continuum if energy conduction is important.

Taguchi argued that the total costs at the point of production about the point of consumption should be minimum for good designs and this should be the goal of product development. He introduced a 'loss function' as an attribute of the product design, which had to be minimised to achieve robust designs. Taguchi suggested that the following sequence of events in his design model, to achieve robustness (Taguchi 1986):

- System design – the physical embodiment of the functional requirements of the product, where special engineering and scientific knowledge is applied.
- Parameter design – the process of identifying the optimal settings of various parameters under the control of the designer to limit variation.
- Tolerance design – involves the control of the variation in critical parameters when everything else has failed to control the variation of performance within the required limit.

Matousek recommends the following systematic working plan as the most practical for a designer (Matousek 1963) p 27:

I. Exact formulation of problems and defining of all questions relating thereto.

II. Setting out of all possible solutions capable of providing the action called for in I into a diagrammatic form (basic Design) and selection of the optimum solution.

III. Selection of the most suitable material.

IV. Consideration of production engineering problems.

V. Deciding on the most appropriate form design.

VI. Ascertaining the overall cost.

Overall cost always decides the final form taken by the work. If the cost aspect is unsatisfactory it will be necessary to re-examine the situation in the sequence:

Material→manufacture→form→cost

In considering product design for manufacture and assembly, Boothroyd Dewhurst and Knight use the term 'design' to refer to the detailing of the materials, shapes and tolerance of the individual parts of a product. This activity starts with sketches of parts and assemblies and progresses to the drawing board or CAD workstation where assembly drawings and detail part drawings are produced (Boothroyd, Dewhurst et al. 1994) p 2.

4.3.4 Descriptive design models

Descriptive models cover the processes, strategies and problem-solving methods that designers use, usually emphasising the importance of generating one solution concept early in the process. This solution goes through a process of analysis, evaluation, refinement and development. Examples of the models of March (March 1984), Matchett (Matchett and Briggs 1996) and Gero (Hybs and Gero 1992) are given by Evbuomwan (Evbuomwan, Sivaloganathan et al. 1996) p 313.

4.3.5 Computational design models

Computational models are the basis of computer-generated design solutions, and hence lie within the boundaries of the prescriptive and descriptive models above. Although rapid advances in computer techniques enable repetitive or iterative tasks to be performed quickly, the human thought processes on which they are based remain the same. For the purposes of this thesis, they will not be examined further, except where they provide tools such as design-for-manufacture analysis and support.

4.3.6 Generic design model

In order to look for common elements in design models, the phases or stages of 22 design models were tabulated and compared in a two-dimensional table (Table 4.1).

Table 4.1 Comparison of Design Model Stages

Model Author	**Model Phases/Stages**						**Remarks**
	1	**2**	**3**	**4**	**5**	**6**	
Archer L. B. (1984)	Programming	Data collection	Analysis	Synthesis - outline design proposals	Development of prototype designs; validation studies	Communication: preparation of manufacturing documents	These 6 stages grouped into 3 phases - analytic, creative and executive

	Model Phases/Stages						
Asimow M. (1962)	Feasibility study	Preliminary design	Detailed design				Each of these 3 stages is in steps of analysis, synthesis, evaluation, decision, optimisation and revision
BS 7000 Part 1: (1990)	Feasibility study - Design brief	Conceptual design - concept drawings	Embodiment design - layout drawings	Detail design - detailed product definition	Manufacturing instructions	Post design support	Derives from Pahl and Beitz and French
BS 7000 Part 2: (1997)	Feasibility phase	Concept design	Embodiment design - general arrangement	Detailed design-product specification - pre-production prototypes	Finalisation for manufacture and delivery - product package	Design support for manufacture	Includes refs to Pugh, Wheelwright and Clark, Topalian, and J. C. Jones
Cross N. (1991)	Clarification of objectives - objective tree method	Establishing functions - function analysis	Setting requirements - performance specification	Generating alternatives - morphology chart to generate complete range	Evaluating alternatives - weighted objectives method	Improving details - value engineering method	
French M. J. (1971)	Analysis - identify need as precisely as possible	Conceptual design - broad solutions schemes	Embodiment of schemes - develop into greater details	Detailing - selected scheme worked into finite details			Model shows feedback between the first 3 phases
Gero J. S. (Hybs & Gero 1992)	Formulation of design brief or specification	Analysis	Synthesis	Design description	Simulation of environment	Manufacture of product	Evolutionary design model - iterative cycle
Harris A. J. (1980)	Appreciation of the task - needs, resources	Conception - tentative form, material and construction method	Appraisal of concepts - critical examination	Decision - criteria may include simplicity, distinction and construc ability	Checking and elaboration - models built and tested, analytical techniques applied, drawings and text produced		Used for civil engineering design teaching

	Model Phases/Stages						
Hubka V. (1992)	Elaboration of assigned problem - clarify specification	Conceptual design - functional structures - concept	Laying out- preliminary layout - dimensional layout	Elaboration - detailing			6 steps in 4 phases
Jones J. C. (1962)	Analysis	Synthesis	Methods of evaluation -- to detect errors	Evaluation for operation manufacture and sales			Evaluation by manufacturing is a late occurrence in this model
Krick E. V. (1969)	Problem formulation	Problem analysis - specifications, constraints and criteria	Search - generation of alternative solutions	Decision - evaluation, comparison and screening	Specification - detailed documentation, drawings, reports etc.		
March L. (1984)	Productive reasoning - creates nove composition	Deduction - design theories predict performance	Inductive reasoning - evaluates suppositions				Cycle is repeated to refine as necessary
Marples D. L. (1960)	Synthesis - search for possible solutions	Synthesis - examination of possible solutions	Evaluation of viable solutions	Decision on particular solution			'Marples tree'
Matchett E. (1996)	Thinking with outline strategies	Thinking in parallel planes	Thinking from several viewpoints	Thinking with concepts	Thinking with basic elements		'Fundamental Design method' (FDM)
Matousek R. (1963)	Problem - define all questions	Basic design - set out possible solutions - select optimum	Material - select most suitable	Manufacture - consider production engineering problems	Form design - decide on most appropriate	Overall cost - ascertain	
Pahl G. and W. Beitz (1984)	Clarification of the task	Conceptual design	Embodiment design	Detailed design			
Pugh S. (1990)	Market (user need)	Product design specification	Conceptual design (note: concept may come before specification for fixed or static concepts)	Detailed design	Manufacture	Sales	Total Design activity model shows these 5 core elements within iterative framework of resources, constraints and analysis

	Model Phases/Stages						
Suh N. (1988)	Problem definition- functional requirements (FRs) and constraints	Ideation - conceptualising and devising a solution	Analysis of proposed solution - rationality and consistency with problem definition	Checking fidelity of final solution to original needs			Axiomatic design model: seeks independence of FRs and minimum info content of design
Taguchi G. (1986)	System design - physical embodiment of of functional requirements	Parameter design - optimal settings to limit variation	Tolerance design - control of critical parameters				Integrates quality into early design stage – 'quality loss function'
VDI 2221 (transl. by Wallace, K. L. 1987)	Clarification and definition of design task	Determination of required functions	Search for solution principles	Division of solution into realisable modules	Develop-ment of key modules into set of preliminary layouts	Develop-ment of definitive layouts and final documentation	
Watts R. D. (1986)	Analysis	Synthesis of design concepts	Evaluation o feasibility, optimisation revision and communication				Performed cyclicly from abstract to concrete levels (Helical model)
Wheel-wright S. and K. Clark (1992)	Concept development - product architecture - conceptual design - target market	Product planning - model building - small-scale testing - investment/ financial	Product/ process engineering - detailed design of product and Tools/ equipment - building/ testing prototypes	Pilot production/ ramp up - volume production prove-out - factory start-up - volume increases to commercial targets			Typical phases of product development

Allowing for the use of different terms to describe essentially the same activity, and for the incorporation into many models of effectively a third dimension to provide for iteration or the influence of constraints, there was a general commonality in the approaches.

For the purpose of this thesis, a generic design model was assumed that contained the following elements that were common to the methods in Table 4.1:

- clarification of requirements/task concept;
- development of the conceptual design;

- embodiment or layout design;
- detailed design;
- manufacturing instructions and production documentation.

4.3.7 Design methods

A number of design aids, tools and support systems are used during the various stages of the design process, in order to arrive at a realisable product and/or process. These tools and aids are what are generally regarded as design methods. They help to formalise and systematise activities within the design process and externalise design thinking, i.e. they try to get a designer's thoughts and thinking processes out of the head and into charts and diagrams (Evbuomwan, Sivaloganathan et al. 1996) p 315.

Hubka defines a **design method** (Hubka 1983) as:

> "Any system of methodical rules and directives that aim to determine the designer's manner of proceeding to perform a particular design activity, and regulate the collaboration with available technical means."

4.4 Manufacturing information requirements for design

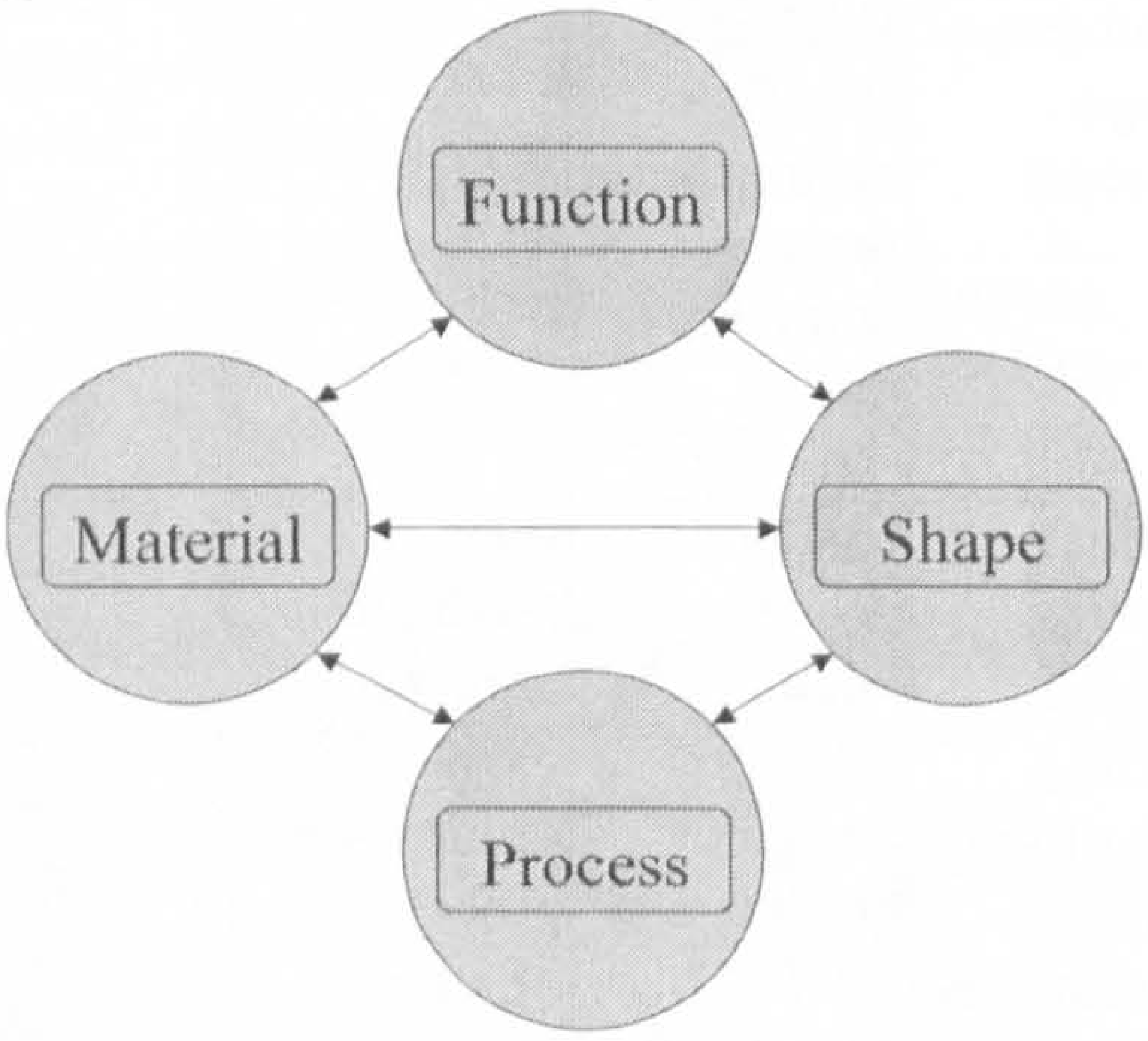

Figure 4.1 Interaction of function, material, process and shape (Ashby)

Ashby describes how function, material, shape and production process interact, with the aid of the diagram shown in Figure 4.1. He emphasises the importance to design of knowing the material attributes, i.e. its physical, mechanical, thermal, electrical, environmental and economic properties (Ashby 1999 p 2).

Chen researched the basis for a knowledge-based computer tool for providing designers with manufacturing information. He found that designers were usually familiar with only a few methods of production and tend to design for these, as they felt confident with them. When they needed to apply unfamiliar manufacturing methods, they often encountered two problems: they did not know which manufacturing issues were important, and they did not have sufficient manufacturing information to address the issues (Chen 1998) p 2.

Chen investigated the characteristics of manufacturing information required in each design phase, using a set of phases based on those of Pahl and Beitz. He assumed that this information depended on the specific design-for-manufacture focus of that phase and on the design information available in that phase as follows (Chen 1998) pp114-118:

- **Task Clarification Phase:** (Production-related requirements) *since no configuration information is generated, designers cannot analyse or improve product producibility.*
  - Supports specifying production-related requirements.
  - Guidance information: checklists of requirements; (measurable) indices for the requirements; and guidelines for using the indices.
  - Analysis information: feasibility and clarity of requirements.
  - Redesign information: identification of defects; actions for correcting defects; and cost impacts of the actions.
- **Conceptual Design Phase** (Configuration information on both joints and components available. Only characteristic assembly and component attributes specified. Provisional rather than determined. Broad rather than specific.)
  - Supports generating producible characteristic configuration.
  - Information on both manufacturing and assembly processes is required.
  - Manufacturing information is seldom required.
  - General information is more useful than detailed information.
  - Class-level information (e.g. casting) is more useful than method level information (e.g. sand-casting).
  - General DFMA guidance that allows a large degree of freedom is very useful during this phase.
  - Information on fatal defects of characteristic configuration, i.e. uncorrectable errors without changing solution principle, is required.
  - Accurate producibility analysis is difficult to generate and of little use.
  - Redesign information on minor corrections is seldom required.
- **Layout Design Phase** (Configuration information on both joints and components available. Information on joints is completed in detail. Information on assembly-related component attributes is detailed and completed. Information on non-assembly-related component attributes is broadly specified.)
  - Supports generating product configuration for ease of manufacture and assembly.
  - Information on both manufacturing and assembly process is required.
  - Due to its high intensity of the generation of configuration information, a large amount of information is required.
  - Detailed information is more useful than general information.

  - Method-level information (e.g. sand casting) is more useful than class level information (e.g. casting).
  - Both general and method-specific guidance is useful.
- **Detail Design Phase** (Configuration information on both joints and components available. All information on components is detailed and completed.)
  - Supports detailing component information for ease of manufacture while maintaining product assemblability.
  - Information on both manufacturing and assembly processes is required.
  - Substantial information on the manufacturing process is needed.
  - Most of the information required is detailed and method-specific.
  - Although general guidance is useful, detailed and method-specific guidance about manufacturing methods is essential.
- **Product Documentation Phase** (Product documents containing design information and production instructions.)
  - Supports document in design information and production instructions.
  - Guidance information: drawing standards; documents standards; and coding systems.
  - Analysis information: feasibility and clarity of documents.
  - Redesign information: identification of defects; actions for correcting defects; and cost impacts of the actions.

Chen defined the manufacturing information (MI) required by designers as being either direct or indirect (Chen 1998) pp 120-122. Figure 4.2 shows his Manufacturing Information Model, as modified by Nowack to include the extended design environment (Nowack 1997) p 137. Both Chen and Nowack were seeking to provide manufacturing information guidelines to designers in an automated manner that could be accessed when manufacturing engineers were not available. Chen defined **Indirect MI** as the types of information needed by designers to address production issues:

- Guidance information, including DFMA principles, important production issues and issue-specific guidelines.
- Producibility information, including information on production feasibility and costs.
- Redesign information, including identification of design defects, specific design changes to correct these defects and evaluation of improvements in producibility.

The above was named 'indirect' MI because it was usually specific to design projects, it was seldom directly available from design handbooks or catalogues and was usually derived from analysis. To generate indirect MI, manufacturing engineers need to be provided with the following types of design information: configuration information, project information and rationale information.

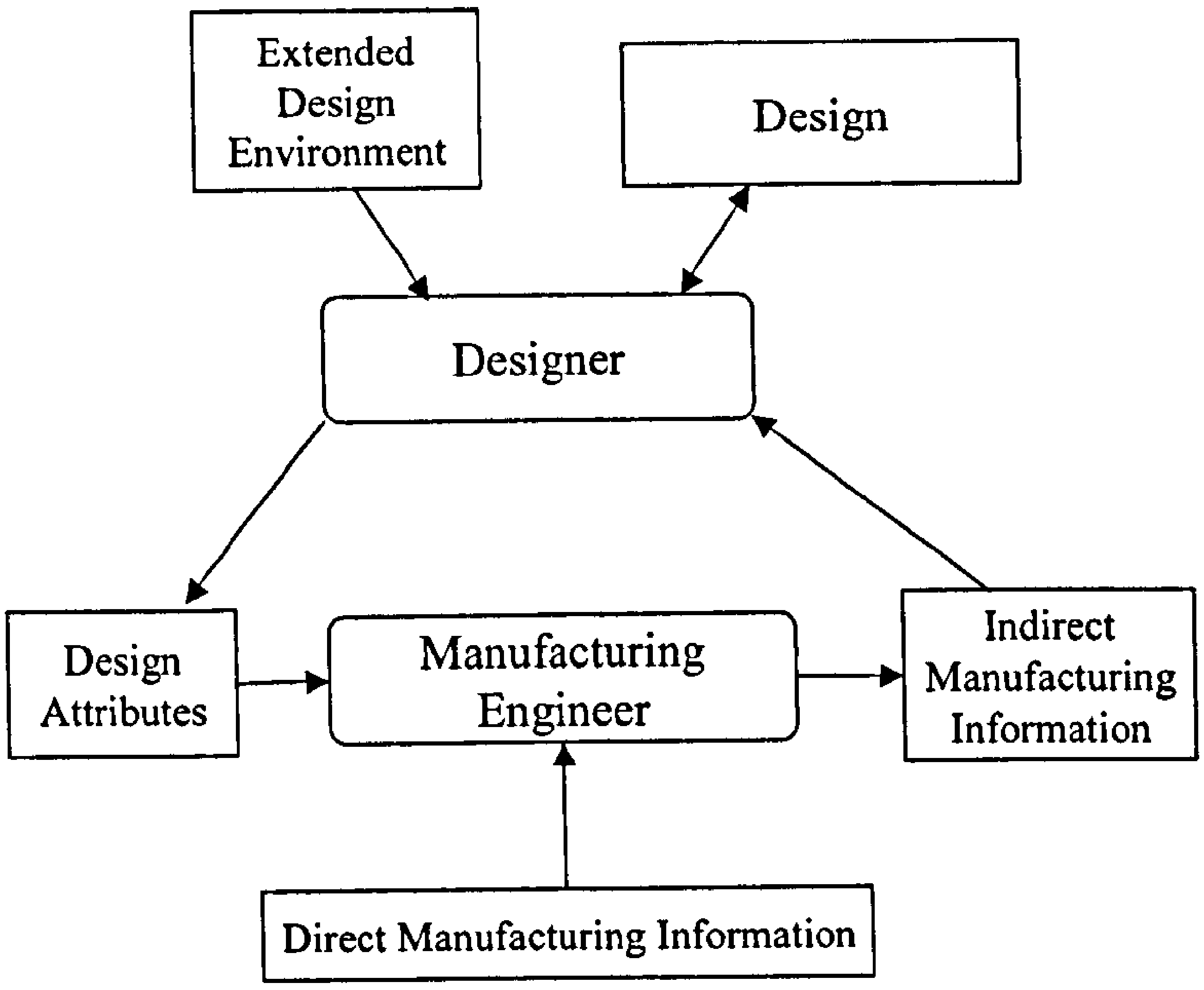

Figure 4.2 Manufacturing Information Model (Nowack, after Chen)

In contrast to indirect MI, **Direct MI** was usually readily available from handbooks and catalogues, and not normally prepared for any particular projects. Direct MI:

- included all information about production methods, manufacturing systems and engineering materials;
- emphasised information about production methods and information on production resources.

The author was privileged in April 2000 to have a brief discussion with Dr Ken Wallace, who had supervised both Chen and Nowack for their PhD work at Cambridge University, referred to in this section. He had been responsible for the translation from German into English of the standard work on design by Pahl and Beitz (Pahl and Beitz 1984). While design guidelines could provide valuable assistance, Dr Wallace accepted that it might be 20 years before comprehensive automated systems could replace entirely the personal input of the manufacturing engineer.

4.5 Sources of Information to Influence Design

Designers are influenced by a number of sources of information to assist them in solving problems and help them to develop manufacturable designs. E.g. Slusher and Ebert recognised two reservoirs of information that project teams used in any design environment: the team's personal knowledge gained from its own experiences, and general design knowledge contained in books, computer databases, organisational documents, and in the minds of designers. If the team's current problem lay outside their existing repertoire, they would extend the search and explore other standard information sources. Only when familiar sources had been exhausted would the team expend additional effort to identify and exploit new information sources. The sources that would be tapped were constrained by knowledge, time, cost and access requirements, and the search limited to accumulating a satisfactory amount of information rather than the maximum (Slusher and Ebert 1992) p 126.

The following sections set out points from the literature relating to sources of information that could influence a designer. Chapter 5 Section 5.3.3 explains how such sources were divided into the five categories subsequently used for analysis: training and experience; standards, textbooks, reports, specifications and procedures; CAD Systems; design for manufacture (DFM) tools and software; and communication and teamworking. For ease of cross-reference, these categories are used as headings here.

4.5.1 Training

Hubka and Eder postulate that, because it is a rational (cognitive) activity, which can be decomposed into smaller (Design) steps, stages and/or phases, designing is teachable, conditioned by the existence of the theory (i.e. Design Science), and the right educational methods and media (Hubka and Eder 1996) p 50.

Training is a source of information and influence for everyone, not just in respect of the technical knowledge possessed by the designer. Drennan emphasises the importance of training programmes in changing people's culture. The right sort of training can help everyone in the organisation, from top management downwards, to change his or her habits and behaviour (Drennan 1992) p 112.

McMahon et al emphasised the importance of designers maximising the quality of information retrieved in the time allocated to information retrieval, by training and personal development to improve the value of personal and group memories. Their ability to connect with the highest quality information available to the organisation should be helped by the provision of suitable information storage and retrieval mechanisms (McMahon, Lowe et al. 1999) p 1653.

4.5.2 Experience

The 'deepest' level of experience was the understanding shown by experienced designers with a wide-ranging working knowledge of the technology and issues in their specialist areas of design, acquired over many years and obtained from a number of projects (Marsh 1997) p 150.

4.5.3 Standards, textbooks, reports, specifications and procedures

From his direct observations of designers in aerospace, Marsh found that the use of formally-recorded information (e.g. reports or other design documentation) was hampered by:

- In many situations, designers were unaware of, and unable to determine, what relevant information existed.
- There was little certainty about what knowledge might be obtained from any documentation obtained – i.e. what would be included and to what level of detail.

These issues, where design processes were constrained by time pressures, were more significant than physical accessibility or convenience of acquisition in governing the consultation of recorded information. Personal contacts were used for getting to most information relating to past design work, existence of design alternatives and recommending approaches to tasks or problems, including finding information from reports or other process documentation (e.g. change control notes, manufacturing concessions). Design reports were not observed to be retrieved directly (e.g. from bookshelves or filing cabinet) except by the author of a given report. Speculative searches to establish what, if any, documentation could be located and might be relevant were not seen to occur. Therefore where documents were retrieved directly, search time was minimal because the source was known and familiar (Marsh 1997) p 159.

Standards, textbooks, reports, specifications, procedures and databases used by designers are, by nature, based on historical information. If they are not kept up to date, or if consulted in the wrong context, they may provide false guidance.

4.5.4 CAD Systems

McMahon and Browne provide a useful guide to the principles, operation and use of computer-aided design (CAD) systems, and their interface to computer-aided manufacturing (CAM) (McMahon and Browne 1993).

Baker describes current CAD Systems as ‘reactive’, because a designer typically has only a fraction of the information he needs when he starts a job. For example, he may know that certain components of a product will be milled, but he probably does not know which machine will be used or what the travel limits of the tool are. These factors might affect the design. But the designer does not find this out until the design has been sent on to Manufacturing. They alert him to a problem regarding tool travel and then he reacts, redesigning the part as necessary. Baker goes on to advocate a ‘predictive’ CAD system of the future that would allow designers to incorporate manufacturing requirements and evaluate product performance early in the design process, when they could make those changes inexpensively, shifting the design engineer’s role from one of reacting to that of predicting, or meeting in advance all of the requirements for the product. This cannot be done by a commodity geometry-centric CAD tool, but requires a high-end CAD system supported by a wide range of integrated, advanced knowledge-capture technologies. Knowledge-enabled CAD, the foundation of the predictive engineering environment, represents the next big step in the evolution of mechanical CAD technology. This is comparable with the change from drawing-based technology to feature-based digital models or the more recent shift to process-based solutions. The latter came about as the CAD vendors developed CAD/CAM/CAE implementations called ‘process threads.’ A process thread supplies all the tools necessary to move an idea from concept to finished product with no data translation (Baker 2000) p 96.

4.5.5 Design for Manufacture (DFM) tools and software

Checklists, guidelines, geometry-checking software, context-sensitive manufacturing advice software, and cost-calculating software are all examples of tools that may be used to assist in improving the producibility of designs.

4.5.5.1 Checklists

Lempiäinen regarded paper-based checklists as the most-used and easily-accessible way of utilising DFM methods. The basic lists could be easily created, copied and modified according to the product families and their special problematics. This tool was extraordinarily cheap. The number of checklist questions was usually very limited, so the motivation for using this in a new product development project was rather high. It was easy to generate new very detailed questions, as the part families often had special design and production characteristics (Lempiäinen 1997).

Gruenwald provided guidelines on the purpose and use of checklists (Gruenwald 1991):

- The discipline of the new product checklist is to be certain that no consideration is overlooked. It is not to assure that all are implemented.
- Countless new product failures are attributable to missed, ignored, misplaced, or purposely gap-jumped essential steps or information. Almost every flop finds its cause in something that appears obvious after the fact and, in many cases obvious in the very early, least-costly phases of development. A comprehensive checklist system provides an early, regularly-modified detailed perspective.
- The checklist should be comprehensive, including an evaluation of management, personnel, facilities and resources... and also provide space for appended areas that may be unique to your specific business.
- It is critical that the checklist used accommodates all affected and affecting parties within the organisation. Each business is built differently, whether it be maker, processor, builder, servicer or seller, or any combination of these. It will be made up of any number of different departments, each with a different function. The checklist must allow input from all functions within the organisation.
- Gruenwald's checklists set out the subjects for consideration as headings for the rows, and each business functional department was listed in the column headings. In this way, they could prompt inputs both from those departments most closely involved in the new product development and from less likely sources.

4.5.5.2 Guidelines

Manufacturability guidelines have been published for a variety of manufacturing processes. Minis et al reviewed a number of different approaches to evaluate the manufacturability of a given design, and classified them as follows:

- **Direct or rule-based** approaches evaluate manufacturability from direct inspection of the design description: design characteristics that improve or degrade the manufacturability are represented as rules, which are applied to a given design to estimate its manufacturability. Most existing approaches are of this type. Direct approaches do not involve planning, estimation, or simulation of the manufacturing processes involved in the realization of the design.
- **Indirect or plan-based** approaches do a much more detailed analysis: they proceed by generating a manufacturing plan and examine the plan according to criteria such as cost and cycle time. If there is more than one possible plan, then the most promising plan should be used for analysing manufacturability – and thus some plan-based systems generate and evaluate multiple plans. The plan-based approach involves reasoning about the processes involved in the product's manufacture.

The direct approach appears to be more useful in domains such as near-net-shape manufacturing, and less suitable for machined or electromechanical components, where interactions among manufacturing operations make it difficult to determine the manufacturability of a design directly from the design description. To calculate realistic manufacturability ratings for these latter cases, most of the rule-based approaches would require large sets of rules (Minis, Herrmann et al. 1999) p 384.

Nowack discussed the use of design guidelines as follows (Nowack 1997) p 59:

- A recent test revealed that the information accessed was often irrelevant in the eyes of the designer.
- The primary use of design guidelines was for evaluating a design. Ackers et al noted that design guidelines were primarily used to check for omissions. Experienced designers were concerned about overlooking important issues and found that the database did not provide new information (Ackers et al. 1995).
- A possible reason for Ackers observing little synthesis was because the tree structure in this set of guidelines made rapid retrieval difficult, especially when competing against the designer's mental store of guidelines.
- Novice designers had different problems – often they found guidelines that appeared to be relevant, but the designer lacked the requisite knowledge to apply them (Ackers et al. 1995). Nowack suggested 'How'/'Why' & 'Requires' relationships could help novices.
- A major problem was that the guidelines did not bring design context to bear on guideline selection.
- T. Lawlor-Wright also noted this problem on the early industrial tests of guidelines in Design for TestAbility project at the University of Salford, which led to the guidelines being provided with textual and graphical explanations (Lawlor-Wright 1997).

4.5.5.3 DFM and DFA Software

An increasing number of software programmes is available to assist designers in applying guidelines and checklists. Leaney compared from case experience the application of Boothroyd and Dewhurst Inc's (BDI) DFMA, Hitachi Assemblability Evaluation Method (AEM), and Lucas (CSE-TeamSET) (Leaney 1996a). Herrera describes the application of BDI DFMA on the Design of the AH64D Helicopter (Herrera 1997). It was noted that 'DFMA' is a registered trademark of BDI (Boothroyd, Dewhurst et al. 1994) p 2, but is often applied by other authors to describe a variety of software tools for DFM and DFA.

Minis et al regard traditional manufacturability evaluation approaches that consider typical costs and processing times (like DFMA20) as useful for comparing the relative cost and time when the manufacturing process is known and standardised. However, these approaches are insufficient and may lead to poor designs when there exist alternative process plans and a choice of subcontractors that have different capabilities (Minis, Herrmann et al. 1999) p 387.

In examining existing DFM and DFA tools, Chen concluded that most support methods for DFM and DFA were developed in isolation, and should be integrated to avoid shifting problems and costs between assembly and manufacture. Most computer-based DFM and DFA tools were not integrated into CAD systems – they relied on the designers' input of design information: often tedious and ambiguous. Therefore designers were discouraged from using the tools. Time-consuming search processes and the inability to provide precise immediate help for specific problems hampered the application of DFMA guidelines. Few methods were capable of providing redesign information after a producibility analysis, i.e. they could not show how designs could be improved. Research in knowledge acquisition and organisation was still needed, especially in practical ways to get information to designers in a useful and timely fashion (Chen 1998) p 36. The validity of Chen's point regarding the benefits of looking at DFM and DFA together is accepted. However, the earlier that Design is alerted to potential problems in manufacture of parts, the sooner any conflict with assembly considerations can be identified. The research for this PhD thesis is focused on DFM and Producibility in the context of optimising the design to avoid problems in the manufacture of individual parts, but in many cases the factors involved in allowing part-manufacturing problems to reach the shopfloor may apply equally to assembly problems.

There is much scope for more widespread adoption of suitable tools by industry, in particular small and medium enterprises (SMEs). Bush and Rowbotham reported that often SMEs were not aware of many of the best design practices and so were not able to meet the demand for continuous improvement of the products. However, it was considered that if novice designers could successfully utilise design tools like QFD and DFMA to achieve improvements in design quality, then SMEs had no excuses for ignoring the benefits they could bring to their own product development activity (Bush and Robotham 1999) p 364.

Leaney highlighted lessons from the Japanese approach to the integration of design, manufacture and assembly. Nissan recognised that the strict division of jobs according to function and duties of engineers in America and Europe has traditionally made it difficult to feed back information from the factory floor to the design process and carry out tasks jointly as done in Japan. Nissan considered that the use of design for manufacture and assembly tools, by themselves, did not appear to be a method for aggressively incorporating manufacturing needs in the product design because product design engineers could only guess what the impact of a product design might have on the manufacturing processes. In Japan the product design engineers were responsible for vigorously collecting from the production engineers all the information needed to execute designs for manufacture and assembly and for securing the latter's active involvement in the product design process. Production engineers for their part were responsible for presenting the production requirements in conjunction with conceptual studies of the manufacturing processes (Leaney 1996b) p 181.

DFM software has limitations. Hubka and Eder describe a DFM computer program that can augment and partially replace the advice and co-operation needed in concurrent engineering, to design the product and the manufacturing process at the same time. Manufacturing enters and maintains its expertise in this knowledge-based system, and designers call on the expertise when needed. However, face-to-face negotiations are still important, not just because the system can only maintain a limited range of expertise, but especially because personal interactions can improve the quality of considerations and ideas (Hubka and Eder 1996) p 144.

4.5.6 Communication

Francis defines communication as: "the medium through which managers lead, direct the activities of others, harness human creativity, co-ordinate specialists and control activities, and understand the needs and wants of those who work within the organisation and those who use the organisation's goods or services" (Francis 1987) p XI. It is to be expected from this that communication would be a relevant factor for a very wide range of issues. It will be seen in Chapter 5 that a number of aspects of communication were viewed as the reasons for problems, in addition to the use of communication to provide designers with sources of information.

Drucker asserted that the effectiveness of an information system depended on the willingness and ability to think through carefully what information was needed by whom for what purposes, and then on the systematic creation of communication among the various parties. The effectiveness depended on the pre-establishment of communication (Drucker 1973) p 489.

Ashkenas et al describe the importance of aligning the channel, or means for sharing information, and the message. When the channel matches the message, communication is improved. For example, memos, videos, and policy statements are all important channels for factual information. However, one-on-one or small-group meetings are much more useful channels for information meant to help employees change behaviour. Aligning the purpose and the medium allows managers to share information effectively, while misalignment produces communication failures. In one firm, managers held weekly staff 'communication meetings' where each person described what he or she had done and would do that week. Although the information was useful, most staff members resented the time required when the same information could have been shared more efficiently through static media.

Ashkenas et al povide the following guide to alignment of purpose and channel, in order of appropriateness for sharing factual information or shaping behaviour:

- Face-to-face (one-on-one) – best for shaping behaviour;
- Symbolic (meeting, rally);
- Interactive media (telephone, voice mail, fax, e-mail);
- Personal static media (letter, memo, report);
- Impersonal static media (bulletin, flyers, newsletter, video) – best for sharing information.

For example, if the purpose of communication is primarily to share factual information, then bulletins, flyers, and videos can be used successfully. Federal Express, for example, produces daily videos of the previous day's performance to pass along information to all employees about work flow. Conversely, if changing employees' behaviour is desired (for example, employees might need to be informed about a new performance assessment process), a memo is not the right way to communicate. Such changes require some personal contact that makes employees part of the change process.

Each organisation needs to decide what formats are best for it – reflecting its own resources and information collection systems, and the level of frequency that makes sense for its people (Ashkenas, Ulrich et al. 1995) p 75.

Drisis reported the results of a global mechanical designer survey that took place in Nokia Mobile Phones Research and Development Centres. The target of the survey was to find the opinions and attitudes of mechanical designers with respect to their working environment, especially regarding computer aided design tools and support. The most interesting (and unexpected) conclusion from the survey was that the biggest problems identified were not connected to CAD software and directly related tools. These seemed to have reached a good level of functionality and ease of use, so that they did not present any big problems for the daily engineers' work, after an initial learning period. The biggest barrier was a cultural/mental and not a technical one: although the infrastructure was there, the designers still had difficulties in finding the information they needed. Communication in collaboration with others was therefore not as good as the tools used would suggest. It seems that the human way of acting and thinking cannot always keep pace with the latest changes in information technology (Drisis 1999, p 570).

4.5.7 Teamworking

Swink et al emphasised that teams provide the primary integration mechanism in CE programmes, and three types of teams appeared frequently in these projects: a program management team, a technical team, and numerous design-build teams. Depending on the project's complexity, an integration team may be needed to consolidate the efforts of various design-build teams. Task forces also may be formed to address specific problems, such as investigating an emerging technology. Some projects emphasised collocation and face-to-face communication. Others relied on phone conversations, documents, and electronic mail. Projects focusing on design quality relied on formal presentations and periodic review meetings. Projects emphasising development speed required frequent, informal communications. Programs addressing design quality required extended product definition and performance testing, with input from design engineering, marketing, and customers. Efforts to reduce development time involved small, informal teams led by design engineers and managers. Aggressive product cost goals necessitated intensive interaction between product designers and manufacturing personnel. Highly innovative products required early supplier involvement and joint engineering problem solving. Formal design reviews and shared design data systems aided information sharing between internal and external design groups. (Swink, Sandvig et al. 1996).

GP Pisano expressed concern that the speed of internal and external changes of an organisation asked for a complex mix between parallel and sequential development strategies. Apart from that, expert knowledge from all over the world was used in these complex creative activities. No longer could creative and decision-making processes be dealt with by using teams that worked together physically. Unity of time, place and action had now become far too time-consuming (Pisano 1997). Loeffen and Wortmann quoted Pisano, and stated that much more effort had to go into making systems a lot more user-friendly to meet the following challenges (Loeffen and Wortmann 2000):

- How to make information that used only to be available for staff members and line managers available for use on the shopfloor;
- How to make information systems user-friendly so that people can get used to them quickly... they do not have time to gain familiarity or take lots of lessons.

4.6 Published shortcomings of CE

Current approaches, as exemplified particularly by Concurrent Engineering, suffer from problems in their practical implementation.

Maslow et al challenge many of the commonly held views on modern management, claiming that the general principles that Drucker and others talk about are for the most part far *too* general. Certainly managing women is different from managing men. They argue that it would not be realistic to apply Drucker's principles in Colombia, Iran, Syria, and South Africa, and that there are many places around the world where only authoritarian management, cracking the whip over fearful people, can work. Authoritarian characters confronted with human relations principles in management based on all sorts of benificent and benevolent assumptions would consider the manager certainly weak in the head and the very least sentimental, unrealistic, etc (Maslow et al 1998) p 43.

Cleetus, who has done considerable work at the Concurrent Engineering Research Center (CERC) set up by the US Defense Advanced Research Projects Agency (DARPA), reviewed the workings of CE and presented some of these shortcomings, as set out in the following sections.

4.6.1 CE lessons

General lessons (Cleetus 1998) p 253:

- CE does not work without a mandate from above.
- CE does not work without a strong team leader.
- CE works best with physical collocation of the entire team.
- Technology-based CE is best achieved by integrating the tools employed by several perspectives.

4.6.2 Teamwork Can Lead to Chaos

Teams, though, result in chaos more often than not. There are many reasons (Cleetus 1998) p 252:

- Teams are often a sham, never destined by their originators to coalesce.
- Teams rarely invest enough in achieving a common vision before setting out on the detailed work.
- Customer focus is more easily stated than subscribed to in practice.

- Teams do not keep practising and working on team processes.
- Co-ordination is not given sufficient importance.
- Motivating factors are geared to recognise individual work, rather than team achievement.
- The leader of the team is not up to the job.

4.6.3 Poor Task Co-ordination

Project management may fail to provide collaboration support for new product development. The difficulty is to comply with techniques for interactive, distributed, task, and data management. There is a need to go beyond the standard metrics of time and cost to provide unique project assessment tools. All the metrics can be evaluated for single tasks, for sub-projects containing several tasks, or for the entire project. Cleetus recommends that (Cleetus 1998) p 254:

- The task network should be visible to all.
- Progress should be reportable by each individual from his or her workplace via computer.
- The data sharing should be via network databases.
- The flow of instructions, drawings, and work authorisation should take place without paper.
- Questions should be handled electronically.
- The whole project history should be stored.

Jaganathan et al describe how computer support for multidisciplinary teams is critical for group decision-making and negotiation, especially over a geographically dispersed network. While systems such as bulletin boards and electronic mail can provide an initial underpinning to support group working, they are very limited and informal. Fundamentally, they only allow for the exchange of messages, although they are being adapted to support brainstorming and group discussions. However, they do not support structured decision group working. Particular features of task-coordination systems to support concurrent engineering include common visibility of activities and data, planning and scheduling of activities, change notification, and constraint management across multiple perspectives. An advanced system could contain a number of teams' membership profiles, constraints, common workspaces and tasks, and so may it possible for a person to belong to any project, serve any role, and participate in all the team interactions at once, without leaving the workstation (Jagannathan, Reddy et al. 1998) p 264.

4.6.4 Lack of Communication and Data-Sharing

As discussed elsewhere in this thesis, lack of communication and data sharing may be the result of cultural and organisational problems, rather than the absence of the technical means to do so. Huang makes the point that co-operation and communication do not simply mean sharing computer workstations and exploiting network facilities. In the same way that design for assembly was once pushed by automation technology, but it is now manual assembly where great savings are achieved, the important factor is human communication and co-operation in contrast to computers (Huang 1996) p 149.

However, where the will to communicate exists, techniques and software to share information include Acrobat, Notes, EDI, Web, PDM, DMS and ISS (Cleetus 1998) p 256. Jaganathan et al describe a number of aspects of technology for information sharing, including the use of Web-based tools and the Common Object Request Broker Architecture (CORBA) standard to promote interoperability between computer platforms using different operating systems and architecture (Jagannathan, Reddy et al. 1998) p 268-270.

4.6.5 Inadequate Record of Design Rationale

Cleetus regards the capture of design rationale as being of prime importance, but the support for this is quite poor in engineering organisations. The best that is done in a systematic fashion is to annotate drawings when they are revised to state on the drawing the nature of the revision and its cause. However, this has many weaknesses in a complex project. However, when it is first made, the drawing does not contain the justification for each of its constituent parts, and that situation will persist through all its revisions. Much of the design rationale and original design intent will never be captured. Further, when a change is made to one part of the product, consequent small changes may need to be made to other parts. Unless the link between the parts is maintained and examined whenever the changes are made, it is possible that a revision will be made that is inconsistent, unsafe, or inefficient. When variant products are designed, what can be changed and should be changed to suit the numerous requirements, and what may not be changed without severe disadvantage and redesign, is not clear. Indeed, a design process involves alternatives that were considered and rejected, and the memory of the unselected alternatives is lost in conventional records, since it may not even have been recorded

The idea was mooted long ago that these things could be cured if only the designers captured their daily work electronically. Many so-called electronic design notebooks (EDN) were prototyped so that the steps of the design work done by individual engineers could be captured in documents with CAD images, analytic results, annotations, design criteria, and so on recorded, along with indexes by which they can be retrieved in future. Since a great deal of product-development work is done on the computer, it might be possible to add the additional support to capture the important results and annotate them without too much added effort for the working engineers, whose aversion to documentation is itself a difficult barrier.

EDNs have not come into vogue, probably because they are still clumsy to use and demand a lot of work for little payoff – a payoff, moreover, that accrues not to the documentor, but to some future engineers on another project. It remains one of the aspects of collaboration that has the least satisfactory support, perhaps because the goal is to encourage collaboration between people over unknown expanses of space and time and with unspecified projects lying in the future (Cleetus 1998) p 257.

4.6.6 Effect of late changes

If a manufacturing problem reaches the shop floor, this means that action is needed before manufacturing can be satisfactorily completed or that an opportunity for improvement will have been missed. The range of actions may include anything from a query for clarification to a major design change for the part. Even a simple query may prove expensive, because the original design team may have moved to another project and the answer may involve extensive inquiries. Redesign is almost certain to be expensive, and good ideas for ease of manufacturing that might have been adopted with little effort at an earlier design stage may be refused because of their effect on costs, timescale, the interface with other parts for assembly, or even the sheer complexity of the change task.

Boothroyd, Dewhurst and Knight quote the figure (from 1989 Munro & Associates, Inc) of over 70% of the final product cost as being determined during design as a reason why careful consideration of manufacturing and assembly should be given early in the design cycle (Boothroyd, Dewhurst et al. 1994) p 2. More recently, Farineau et al quoted 80% of the costs of a project as being determined by decisions taken by the designers (Farineau, Rabinasolo et al. 2001) p 79.

4.6.7 Types of reasons for problems

Chapter 5 Section 5.3 explains the rationale behind the selection of 'human error', 'culture and social', 'knowledge', 'organisation', and 'technical' as the concept categories for the types of reasons for manufacturing problems. The following sections include examples from the literature on the general principles of these subjects.

4.6.7.1 Human Error

This category covers mistakes of commission or omission. James Reason provides a lot of useful background on the subject of human error, e.g. a study that showed that many highly intelligent people, when presented with simple deductive problems, almost invariably got them wrong. This was because their reasoning was governed more by similarity-matching than by logic (Reason 1990) p 39.

McCormick describes a number of types of human errors in system tasks, stating: "people are quite inventive in the kinds of bloopers they perpetrate." He suggests that figuring out what kinds of mistakes people make may help to reduce their frequency or severity (McCormick and Sanders 1982) p 25.

Reason also examined industrial accidents and their causes. Most accidents results from a sequence of events, the last and least manageable part of which may be short lived mental states – a preoccupation, distraction, forgetfulness, or inattention. People will always make errors and commit violations. While we cannot change the human condition, we can change the conditions under which people work so as to make these unsafe acts less likely. Blaming people for their errors – though emotionally satisfying – will have little or no effect on their future fallibility. Since errors are largely unintentional, is very difficult for management to control what people did not intend to do in the first place (Reason 1997) p 153.

4.6.7.2 Culture/Social

In contrast to errors, which are unintentional, Reason also discusses intentional violations of procedures or accepted behaviour. He regards violations as social and motivational problems that are best addressed by changing people's culture – norms, beliefs, and attitudes – on the one hand, and by improving the credibility, applicability, availability and accuracy of the procedures, on the other. He warns that violations act in two ways. First, they make it more likely that the violators will commit subsequent errors and, second, it is also more likely that these errors will have damaging consequences (Reason 1997) p 153.

Drennan defines culture as "how things are done around here". This is made up of a number of elements. Over time, people develop ways of handling the organisation and this becomes the 'accepted' way of doing things. Methods of work tend to get repeated, supervisors make them procedures and they are then taught to subordinates. These become habit and become part of the organisation's personality. Attitudes are also part of culture. Attitudes show in how an organisation treats its customers, suppliers and employees. The standards laid out in Personnel Practice Manuals are not necessarily real culture. Real culture is what employees see fellow workers do and what they find their managers accept. Culture is what is *typical* of the organisation, the *habits*, the prevailing *attitudes*, and the grown-up pattern of *accepted* and *expected* behaviour. Culture does not grow overnight, and cannot be changed overnight either (Drennan 1992) pp 1-4.

Ranky regards Concurrent Engineering as very much an issue of team management, people, communications, sound technology and 'culture'. The most important principles are about the total design-and-manufacturing cycle and implementing it using appropriate (not necessarily the latest) technologies and excellent people equipped with multidisciplinary skills. The heart of a problem is that engineers in design, manufacturing, quality assurance and maintenance do not speak the same language. Most of the obstacles are cultural and organisational. New technologies provide the excellent communication systems that the small family business always had, as well as new methods and tools for creating, analysing, testing and implementing products that the customers need. Both the Concurrent Engineering team and the management need to be committed to the new methods and must be prepared to change the company culture to take advantage of them (Ranky 1994) pp 23-27.

For the purpose of this thesis, the term 'culture/social' is used to cover the more subjective aspects of culture and social issues. More objective matters, which could be regarded as 'organisational', have been segregated and put into a separate category (see below) to avoid creating a broad 'culture and social matters' category that included more than half the reasons considered.

4.6.7.3 Knowledge

Knowledge plays a vital part in 'getting things right'. Miller and Morris explain how capability is affected by tacit and explicit knowledge. Knowledge comes about through the integration of information derived from data, plus theory that puts the information in the proper context, plus experience of how things work in the real world. This process of integration is also called learning (Miller and Morris 1999) p 76.

This category covers problems that occur through lack of knowledge.

4.6.7.4 Organisation

Organisation covers the more objective aspects of Company culture, such as procedures, and who is responsible to whom for what. It includes facts, such as the physical problems resulting from a firm operating from two sites. However, subjective matters such as the reluctance of people to talk to someone from the other site would be covered under the Culture and Social heading.

Duffy and Salvendy found that effort spent in terms of time determining the Task and Work Structure was the largest predictor of success in implementing concurrent engineering (Duffy and Salvendy 1995).

4.6.7.5 Technical

Technical problems are those that relate to the equipment or software rather than the people using it. For example, a mismatch that prevented model data from one CAD system being correctly represented on another. Owen concluded that, despite all the expertise utilised in generating STEP protocols, problems would arise even when data exchange was undertaken using two performance-tested processes of a well-defined standard written using formal methods. He considered product data exchange was unlikely to become 'appliance' or 'black box' technology in the near future, if ever (Owen 1997) p 131.

4.7 Gap in Research

4.7.1 Gap in the literature

Engineering management literature is largely tied up with hard issues such as procedures and practices. Where soft issues such as human factors are covered, they are usually grossly oversimplified – for example, "establish early contact with suppliers."

If an industrial firm sought to tackle its manufacturing problems by optimising its CE and DFM processes, it would find that many different CE and DFM solutions were available, but no single approach would necessarily best fit the circumstances of their own products, projects, people and manufacturing requirements. The potential answers to any particular problem were likely to be spread among various sources and methods.

The author was unable to find any approach that started with a comprehensive guide to potential manufacturing problems and then proceeded to relate them to possible causes. In attempting to fill this gap in the research, the author worked to provide a guide to act as a key to 'decode' the manufacturing problems that previous research 'coded' into various sources. An analogy is with addressing the problem of finding a list of remedies for a particular illness: a medical directory where you could look up the illness to find the medicines would be more useful than a directory of medicines that showed all the illnesses each would treat. Both directories have their uses, but each is of limited value if you need the other.

To identify the gap in research, the author adopted Silverman's critical approach to the literature review by answering questions under the following headings (Silverman 2000) p 231:

4.7.2 What do we already know about the topic?

Concurrent engineering techniques have been developed with the intention of bringing together functional disciplines to allow downstream activities such as manufacturing to influence upstream activities such as design. Producibility, or manufacturability, is a recognised consideration for design and is included in some form in a wide range of models of the design process.

Recent research (Nowack 1997, Marsh 1997 and Chen 1998) includes examination of the requirements of designers for manufacturing information, how designers use their experience, and how design guidelines on manufacturability can be presented on a database. This work towards providing manufacturing information to designers in a readily accessible form reflects recognition of the limited time that designers are observed to spend on searching for information.

4.7.3 What do you have to say critically about what is already known?

Manufacturability guidelines, however presented, are necessarily derived from existing processes and previous applications. They may not cover the required geometrical features, processes, materials and local conditions – and hence may not be applicable directly to the current design context. A designer may have to expend considerable effort loading data into a DFM software tool in order to obtain an assessment of the manufacturing cost, then repeat the exercise to compare alternative design solutions. An 'expert system' may be a valuable support tool, but is unlikely to provide the complete answer (e.g. Gammack and Jenkins 1997, p 86).

Typical textbook approaches to concurrent engineering and design methods are prescriptive, setting out the elements of what is needed to ensure a successful design-to-manufacture process. Potential problems and obstacles may be mentioned, but coverage is often in general terms. For example, Prasad emphasises the early involvement of suppliers as being critical in providing vital inputs and in influencing the product's design as it evolves (Prasad 1996 p 174), but does not include amongst his barriers to concurrent engineering (Prasad 1997 pp 367-373) any reference to subjects such as trust, contracts and intellectual property rights that may give rise to problems when working with suppliers.

Journal and conference papers tend to highlight particular problems, often gaining material from case studies. Each paper may cover a limited field, but taken together they can provide important illustrations over a wide range of potential problems.

Problems, however, are usually made public only when exposed by a failure or disaster, and those most closely involved will tend to report them in the context of how they were successfully overcome. For a critical examination of the factors that can lead to problems, it is helpful to go beyond the engineering literature and look at the softer issues, such as: human aspects (e.g. Reason 1990 & 1997; de Bono 1971); cultural matters (e.g. Drennan 1992); management, organisation and communication (e.g. Maslow et al. 1998; Miller and Morris 1999; Francis 1987; Ashkenas et al. 1995 and Hargie et al. 1999).

The technology clearly exists (e.g. Jagannathan, Reddy et al. 1998) to enable any form of communication to be provided to promote communication and teamworking. As Smith points out, technology may lower the barriers for cross-functional co-operation

(Smith 1997) p 75, but it does not guarantee the necessary communication will occur: the softer issues may prevent this.

The major gap in the literature is the absence of material specifically linking the reasons for manufacturing problems to the sources of information available to designers.

4.7.4 Has anyone else ever done something exactly the same?

The author could not find anything published that was exactly the same.

4.7.5 Has anyone else done anything that is related?

Several authors cite examples of barriers to DFM and explain their prescriptive methods for developing the organisation to overcome them. Although presented in a manner entirely different from the relationship framework in this thesis, the following two works included material that was particularly helpful. Many of their points contributed to the formulation of ideas used during framework development, and several have been cited in the framework to illustrate factors.

Liker and Fleischer researched the organisational context of design and manufacturing with the hypothesis that in many large US corporations this presented serious barriers to DFM. In the context of primarily traditional, bureaucratic organisations, organisational barriers included structural complexity of the formal organisation, divergent political interests of design and manufacturing, and incongruent cultural values and symbols. Organisational structure complexity meant the numbers, geographical separation, organisational boundaries, and structural differentiation of personnel involved in product and process design and manufacturing (Liker and Fleischer 1992).

Wheelwright and Clark drew on many years of in-depth, systematic, worldwide research to present principles for developing the critical capabilities for speed, efficiency, and quality that have worked well for many fast-cycle firms in a range of different industry sectors in Japan, America and Europe. They contribute many valuable points on aspects such as communication and teamworking, dealing at length with the need to tailor upstream and downstream communications in the product development chain to the nature of the project (Wheelwright and Clark 1992).

4.7.6 Where does your work fit in with what has gone before?

It makes extensive use of existing literature to identify relevant factors.

4.7.7 Why is your research worth doing in the light of what has already been done?

Producibility problems in manufacturing exist despite so much material being available in the literature to provide advice on aspects of the design-for-manufacture process, human factors, culture, management, organisation and communication. It was therefore considered worthwhile to combine the experience from involvement in industrial case studies with that of examining the literature so as to structure the relevant information in a manner that would mean the practical effect of how sources of information and influence can be related to the reasons for manufacturing problems reaching the shopfloor.

4.7.8 What are the critical success factors?

For this research to be successful, the answer to the research question must be:

– complete, within the producibility of mechanical parts boundaries in this thesis;

– presented in a form that can be used both by industrial practitioners to review their producibility processes, and as a basis for further academic research;

– illustrated by references both to literature and the evidence of practical case studies, offering users the opportunity to "resonate with the experience of others and help them make sense of that experience" (Stacey, Griffin et al. 2000) p 203.

Chapter 5 Framework Development

This chapter describes how the data from industrial studies and literature were analysed and used to develop the framework to model the relationships between the reasons for manufacturing problems and the sources of information and influence. This covers steps 9 to 12 of the methodology set out in Chapter 2.

Data from the continuing literature study and the Case Study research were used to help formulate and categorise ideas for the types of reasons for problems in manufacturing and for the sources of producibility information. Several iterations of a two-dimensional matrix were used to test relationships between the categories of reasons and sources, using examples of problems to illustrate the factors involved. The steps taken to develop the final format for the framework are described.

Examples are given of how the framework was populated to show the relationships.

5.1 Approach to the final research question

The final research question had been developed after the author reflected on the experiences gained through the best practice study, AEROEXTN pilot project and the civil aerospace studies. It became, as stated the end of Chapter 3:

> **"Why do manufacturing problems reach the shopfloor when sources of information are available to prevent them?"**

The manufacturing problems and opportunities for improvement listed at the end of Chapter 3 may be regarded as the answers to the questions "what can go wrong?" and "what opportunities could be missed?" To answer the research question, the approach taken was first to identify and group into categories **reasons** for these problems and the **sources** of information and influence available to prevent them, and then to identify **factors** that could relate the sources to the reasons in a **framework** in order to show why the problems reach the shopfloor.

Within the limitations of the research context, the aim of the framework is therefore to present as complete as possible a set of answers to the Research Question 'Why?' It was recognised that the there would be residual problems, which further research could reduce — possibly with an industrial psychologist playing a major part.

5.2 Process for formulating reasons and sources

Figure 5.1 shows the process used to formulate lists of types of reasons and sources of producibility information and influence. The rationale behind the steps shown is set out below; and the implementation of the process is covered in Section 5.3.

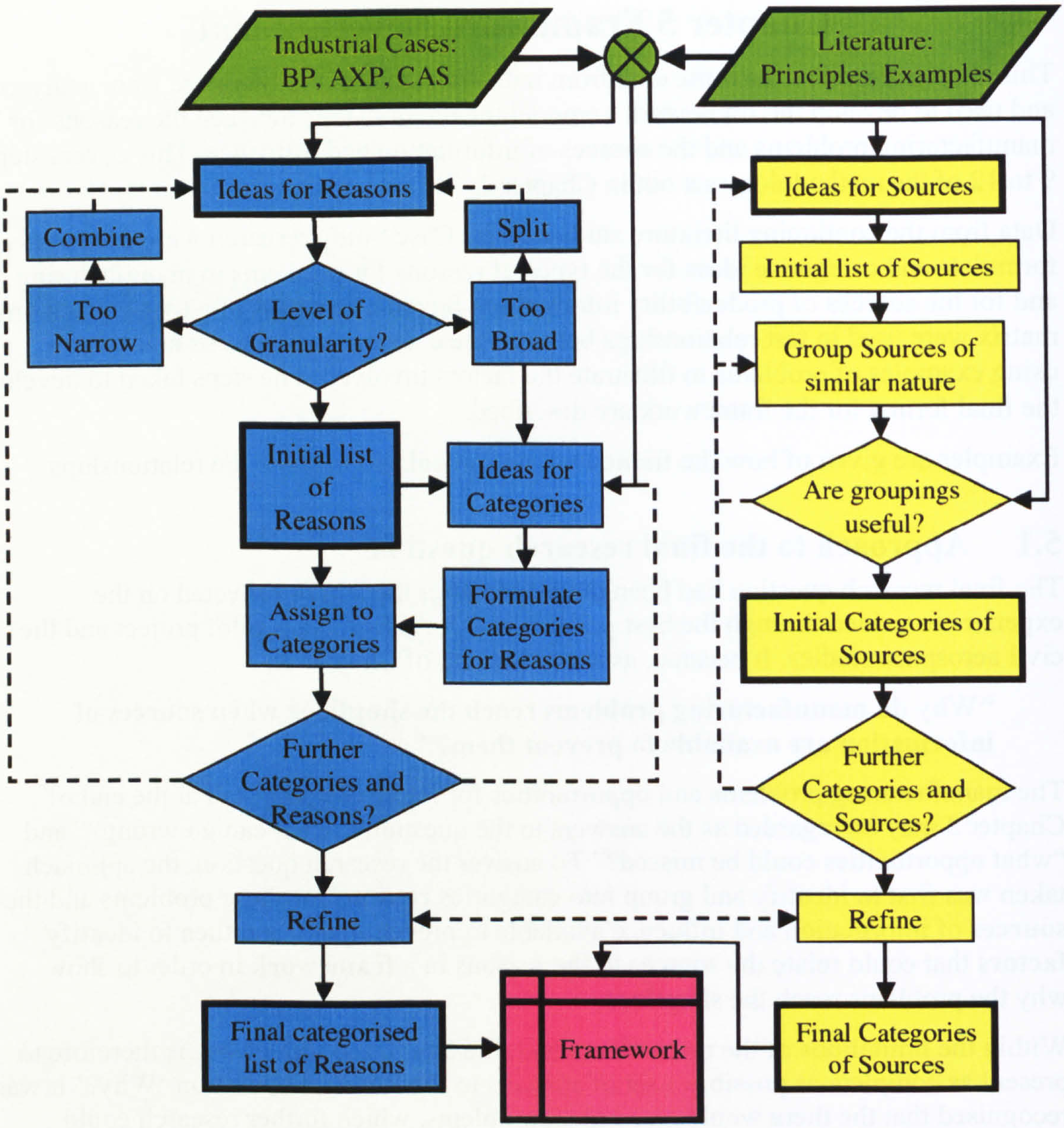

Figure 5.1 Formulation of Reasons and Sources

5.2.1 Input data

The material used to generate and categorise the reasons and sources was drawn primarily from the literature studied and from the research carried out on the industrial cases – AEROEXTN (including the Best Practice study) and the civil aerospace studies, especially the discussions with practitioners in Design, Manufacturing, Quality and Purchasing. The author also attended a number of conferences, seminars and industrial exhibitions relating to design and manufacturing. In addition, valuable advice was derived from discussions with colleagues working on other research projects in the Department of Enterprise Integration.

The following provides an indication of the volume of data considered during the research:

- The minutes of the AEROEXTN project meetings amounted to more than 60,000 words, covering 220 pages. The civil aerospace studies provided a further 12,000 words of reports and minutes. Eight conference papers (included in the list on page iii) were written and presented by members of the academic team.
- The total bibliography consisted of more than 360 books, conference papers, and journal, Web-based and newspaper articles. The thesis as a whole contains 278 citations, referring to 148 different works. The framework of Chapter 6 includes 132 citations, covering 85 different works.

There was some direct read across from the AEROEXTN data, adapting ideas based on specific subjects addressed in the Producibility Interaction model, and the issues and enablers used in developing the CE template. However, much of this work concentrated on the 'hard' technical aspects concerning the mismatch of product and process rather than the 'soft' considerations such as motivation and co-operation. Both hard and soft areas are important, but the subjective nature of the latter can make it particularly difficult for management to recognise their effect and know what action to take to improve matters. The approach taken was aimed at generating ideas for reasons and sources that would both illustrate what could go wrong and stimulate thinking about why this could happen.

No specific date limits were set on the material researched, although there was a tendency to place emphasis on the more recent material. However, early books and papers were often found to have an up-to-date message that was still relevant.

5.2.2 Ideas for Reasons

In order to be considered, a reason would have to satisfy the conditions that it should be:

- Relevant to the design-to-manufacture chain in the context of:

  – complex, custom, CAD-designed parts;

  – mechanical machined parts, or composite parts;

  – an organisation large enough to have separate design and (internal or outsourced) manufacturing facilities;
- Capable of introducing or allowing a producibility-related production problem (of the kind set out in Section 3.8.3) that could have been avoided by a change in the design of the part, e.g. by:

  – failing to make information available

  – failing to generate or collect information

  – introducing errors or false information

Ideas that passed the above tests were then considered for their level of granularity, i.e. to ensure that they were not too broad or too narrow in concept. Ideas that were too narrow might cover a single specialised issue that could be combined with others to form a clearer concept with greater generalisability that would be of more use in helping others to recognise its influence. Conversely, ideas that were too broad would not be helpful in providing specific guidance and were better split into separate reasons. However, broad ideas could be considered as possible categories covering a number of types of reasons.

Ideas with the appropriate granularity were likely to have general applicability without justifying a separate category. These were put together to form an initial list of reasons.

5.2.3 Categorisation of reasons

Reasons from the initial list were grouped to form categories, using ideas that came from the literature (e.g. human error) as well as those considered too broad in the granularity test. The aim here was to identify categories that would help to stimulate thought as to whether there should be additional reasons to complete that category, and whether there should be additional categories to complete the field of all possible types of reasons within the context of the research. Additional ideas for reasons and categories generated in this way were fed back for consideration to meet the same criteria as before.

5.2.4 Ideas for sources

Ideas for sources were generated from the input material by addressing the questions:

- How do designers know their business?
- How might designers obtain information on producibility?
- Is the source distinct from other sources in character, or in the way producibility information is made available to Design?

This led to an initial list of sources.

5.2.5 Grouping of sources

From the initial list of sources, the intention was to find a limited number of groups that would be useful for:

- Subsequent company action;
- Sensitising, so as to help identify relevant factors;
- Containing sources of a similar nature, to avoid duplication of factors and help look for common threads.

This resulted in an initial list of categories of sources. The limited number of categories also had the advantage that the number of columns for sources was not so great as to result in an unwieldy representation when it came to constructing the two-dimensional matrix.

This procedure resulted in an initial list of categories of sources. Further ideas for sources identified as a result of considering the membership of each category were fed back for consideration as above.

5.2.6 Refinement and final lists of reasons and sources

Testing the interaction between reasons and sources refined the categorised list of types of reasons and the categories of sources to produce the final lists. This was done using a number of iterations of draft two-dimensional matrices, as described in Section 5.3. In the final form (set out in Chapter 6), a table was constructed for each category of reasons, with each type of reason becoming the heading for a row and each category of source the heading for a column. This framework of tables is shown as the output in Figure 5.1.

5.3 Formulation of reasons and sources

5.3.1 Initial list of reasons

As a first attempt at identifying the reasons for problems, the initial list of 35 possible reasons for problems reaching shop floor covered:

(1) Inappropriate reward system.
(2) Lack of feedback.
(3) Changes in circumstances (manufacturing equipment).
(4) Constraints of CAD system.
(5) Compatibility of CNC tool path generation.
(6) Wrong standards, when correct standards available.
(7) Inappropriate standards – existing standards do not match requirements.
(8) Not cost optimising.
(9) Not optimised for process.
(10) Failure to convey design intent.
(11) Wrong advice given to designer.
(12) Wrong advice given to manufacturer.
(13) Lack of training.
(14) Lack of experience/ability.
(15) Error in database information.
(16) Sub-optimal solution from DFM software.
(17) Lack of knowledge of machine tool behaviour.
(18) Lack of knowledge of work piece behaviour during machining.
(19) Design's error in constructing CAD model/drawings.
(20) Manufacturing's error in reading CAD model/drawings.
(21) Wrong information entered into CNC tape generation programme.
(22) Errors in CNC tape generation software.
(23) Malfunction of machine (e.g. tool breakage).

(24) Machine operator error.

(25) Wrong or defective material.

(26) Lack of teamwork.

(27) Failure to recognise that advice is needed.

(28) Failure to obtain best advice.

(29) Prejudice in Design.

(30) Prejudice in Manufacturing.

(31) Personal antagonism.

(32) Information not shared by Design for commercial/political/parochial reasons.

(33) Information not shared by Manufacturing for commercial/political/parochial reasons.

(34) Communication problems.

(35) Failure to consult/involve third parties (e.g. material suppliers, sub-contractors).

5.3.2 Concept categories for reasons for manufacturing problems

In order to analyse these reasons, they were grouped into categories according to type. They were first separated into '**human**' and '**technical**', which immediately led to the realisation that reasons such as 'communication problems' would need to be qualified further according to the circumstances. For example, difficulty in knowing the right person to contact could be regarded as a human communication problem, while difficulty in translating model data from one CAD format to another would be a technical communication problem.

It was also apparent that far more factors were human rather than technical in origin, so the 'human' category was divided. Since any of the human beings involved in the design-to-manufacture chain could make mistakes, one division could be '**human error**'. The remainder might be regarded as coming into the category of 'culture' covering the way human beings interact with each other, but this appeared too general and would embrace such a wide variety of matters that it would be an advantage to distinguish between the personal and impersonal aspects of human interaction. The personal aspect was termed **culture and social**, to cover how particular individuals or groups of individuals related to others. For example, people who had got to know and trust each other might communicate far more effectively than those who had never previously made contact. The impersonal aspect might include how people were organised and related to each other as members of functional specialisations or teams, and was called **organisation**. This category would include subjects such as work incentives and rewards.

The types of reasons were now grouped under the appropriate category, as shown in Table 5.1.

Table 5.1 Initial Categories of types of reasons

Human			Technical
Human Error	Culture and Social	Organisation	
Wrong advice given to designer. Wrong advice given to manufacturer. Design's error in constructing CAD model/drawings. Manufacturing's error in reading CAD model/drawings. ...	Lack of effort. Lack of teamwork. Rejection of good advice. Prejudice in Design. Prejudice in Manufacturing. Personal antagonism.	Not cost optimising. Not optimised for process. Inappropriate reward system. Lack of feedback	Changes in circumstances (manufacturing equipment). Constraints of CAD system. Failure to convey design intent. Compatibility of CNC tool path generation. ...

As the research proceeded, matters relating to what people knew (or did not know) did not appear to fit comfortably into any of these four categories. This led to the addition of a fifth category, labelled **knowledge**.

Chapter 4 Section 4.6.7 covers general points from literature relating to these 5 concept categories, which helped to clarify the scope of each. These points were useful when defining the categories and deciding to which category each of the 35 reasons should be assigned, and also in leading to some of the factors that were later incorporated into the tables in Chapter 6.

5.3.3 Initial list of sources of producibility information

Ideas for sources influencing producibility information could embrace matters affecting any part of the organisations and functions involved in the design-to-manufacture chain, not just those directly touching the designers at their workstations or drawing boards.

The initial list of sources developed as described in Section 5.2.4 covered:

(1) Training.
(2) Experience.
(3) DFM tools and software.
(4) Standards & procedures (company, national and international).
(5) Specifications.
(6) Technical reports.
(7) Textbooks.
(8) CAD Systems.

(9) Communications.

(10) Teamworking.

5.3.4 Concept categories for sources

Concept categories for sources of information and influence were considered on the basis of grouping factors and considering their utility as described in Section 5.2.5. The reasoning that governed the transition from the initial list of sources to the final list of categories of sources is set out below

Firstly, people are given a job to do and responsibilities to bear by virtue of their **training and experience**. For example, a designer would not be a designer, or a toolmaker a toolmaker, without some training or experience or a combination of both. Although training and experience were considered originally as separate categories, for the purpose of this research it was found more useful to combine them, as training might be needed for those without the right kind of experience, and vice versa. Designers may be hired or selected for a particular project team on the basis of their qualifications and experience. It should be noted that training is used as a general term to cover the acquisition of skills and knowledge from a course of instruction, whether this is undertaken at an educational establishment or in an industrial firm. Training should therefore be regarded here as embracing education in the broadest sense.

Secondly, people can look up formally recorded information in standards, procedures (including company design manuals), textbooks and reports of research or earlier projects. Requirements may be laid down in functional and technical specifications. Conduct may be directed or influenced by company rules and procedures. This concept category might be regarded as 'doing things by the book'. Increasingly, such information may be held in electronic databases rather than on paper, and may contain DFM guidelines. However, specific **DFM tools and software** were regarded as particularly significant for this research, and so were treated as a separate category, and were therefore excluded from that of 'standards, procedures, specifications, reports and textbooks.' Consideration was given to finding a generic title for this category, such as 'Pre-existing design information', or 'Briefing material.' However, it was felt that such terms could be misleading, and retaining the elements **standards, specifications, reports and textbooks** would be more useful in helping to focus the users' attention on the influence that these materials could bear on the design process. 'Procedures' was omitted because it could be considered implicit in company standards, and this resulted in a less cumbersome category title for use as a column heading when it came to setting out the framework tables.

The aerospace industry was now developing designs as 3-D models on high-end CAD systems. Providing manufacturing instructions from such a model might require a lot more than supplying geometrical data for programming numerically controlled (NC) machines or generating automatically produced 2D drawings. Annotations on the model or additional drawings may be needed to define special tolerances or processes. A category for **CAD systems** was adopted to sensitize the author to collect data on matters such as the ease with which designers could generate or change geometry and associated information.

If a person was unaware of information that could improve manufacturability or prevent problems, and it was not brought to their attention by any of the mechanisms in the above four concept categories, then communication would be needed before they could know it or act upon it. Such communication could be by any means and with any person. Teamworking was a very powerful means of sharing information, encouraged by CE, which could also be used to generate solutions to problems where no individual either knew sufficient or had the authority to decide on the best course of action. Consideration was given to creating separate categories for different modes of communication and teamworking, e.g. face-to-face versus telephone, teleconference, e-mail, CAD data transfer, drawings, sketches, facsimile or letter; one-to-one versus meetings or conferences of three or more people. However, it was decided to start with one category of **communications and teamworking** that could be split if this is turned out to be more useful in the light of data collected. As the research progressed, it was found that the need or will to communicate appeared much more important than the mechanism for doing so, although the latter could make a difference in helping or hindering the process. The single concept category was therefore retained.

5.4 Framework to relate reasons to sources

5.4.1 Format development

A two-dimensional table was constructed in the form of Table 5.2 to relate the categories of human and technical types of reasons for problems to the categories of sources of information and influence.

Table 5.2 Relationships between categories of sources and reasons

SOURCES of INFORMATION and INFLUENCE	HUMAN				TECHNICAL
	Error	Culture and Social	Knowledge	Organisation	
Training and Experience					
Standards, Specifications, Reports, Textbooks					
CAD Systems					
DFM Databases and Tools					
Communication and Teamworking					

Several iterations were made to Table 5.2 before arriving at a configuration suitable for presenting individual factors to show how the reasons in each category could be related to one or more of the categories of sources of information and influence. Once it had been decided to retain the sources categories without dividing them, switching the rows and columns became a more satisfactory arrangement that could easily allow the addition of rows as further reasons became apparent. The format adopted is shown as a concept matrix in Table 5.3.

Table 5.3 Concept matrix for relating reasons and sources

CATEGORY of TYPES of REASONS for PROBLEMS	TYPES of REASONS	SOURCES of INFORMATION and INFLUENCE				
		Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking
a	b	c	d	e	f	g
Human error	Reason 1	Factor1c	Factor 1d			
	Reason 2	Factor 2c				Factor 2g
	Reason 3 ... Reason N			Factor 3e		
Culture/ social	Reason 1			Factor 1e		
	Reason 2	Factor 2c				
	Reason 3 ... Reason N	Factor 3c			Factor 3f	Factor Ng
Knowledge	Reason 1	Factor 1c				
	Reason 2					
	Reason 3 ... Reason N	Factor Nc				
Organisation	Reason 1					Factor 1g
	Reason 2		Factor 2d			
	Reason 3 ... Reason N	Factor 3c Factor Nc			Factor 3f	
Technical	Reason 1			Factor 1e	Factor 1f	
	Reason 2	Factor 2c	Factor 2d			
	Reason 3 ... Reason N				Factor 3f	Factor Ng

5.4.2 Populate framework

The 35 reasons for problems from the initial list were entered in the appropriate row within each category. Each cell was therefore related by its position to its type of reason and its source category. Any entry in a cell was stated as a **factor**, to answer the question "what problem of this type (row) might be caused by this source (column)?"

Individual factors were inserted in the form of brief notes in the table to show how one or more sources could relate to each reason. The practical advantage of this was firstly that each cell could be examined to stimulate thought, and secondly that any ideas for factors being considered could be 'pigeon-holed' in a cell and subsequently rearranged. However, these notes made the table expand to such an extent that it was decided to divide it and create a separate table for each category of reasons. As an example, by this stage the table for Human error contained the factor notes shown in Table 5.4.

Table 5.4 Human error table – intermediate stage of development

	HUMAN Error	Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking
a	b	c	d	e	f	g
1	Wrong advice given to designer.	Mistake, based on lack of appreciation of problems or over-simplification*	Wrongly assumed paper information correctly applied to current case			Failure to obtain full background
2	Wrong advice given to manufacturer.	Mistake, based on incorrect or outdated information	Wrongly assumed paper information correctly applied to current case			Failure to convey design intent, or warn of known problems with similar processes or materials on other projects*
3	Design's error in constructing CAD model/drawings	Lack of training or experience to avoid errors or omissions		System not easy to use, and/or difficult to check or verify		
4	Manufacturing's error in reading CAD model/drawings.	Lack of training or experience in interpreting model/ drawings		Model/ drawing difficult to interpret (error-prone)		Poor medium for representation No contact to help or explain interpretation

*Note: the asterisks indicate that there were footnotes to the notes, to expand on what could be fitted in the box.

As an illustration, the first type of reason considered in the category of '**human error**' was that of '**wrong advice given to designer**'. This had been put on the list of reasons because any such wrong advice could lead to a design that was suboptimal, and cause problems in manufacturing. After considering all five of the source categories, three cells were filled as follows:

- **Training and experience** would be relevant when a mistake in the advice given to a designer was the result of lack of appreciation of problems, or oversimplification, that could be related to the training and experience both of those who sought advice and those who gave it. For example, an inexperienced person might confidently state that there would be no problems with a particular process, when they had failed to look closely at the requirement and had not recognised that the part was impossible to make with the existing machinery. A more experienced person would have known what to look for; a more experienced questioner might have probed more deeply, knowing that the design might be beyond the process limits.
- **Standards and specifications** would be relevant because it might be wrongly assumed that paper information correctly applied to the current case. The increasing complexity and variety of standards and specifications that are needed to follow more complex products and processes may cause correspondingly more errors and additional work.
- Failure to obtain the full background or context for the advice that is sought is a failure of **communication and teamworking**. For example, a production engineer might correctly answer questions on precision capability, but fail to point out that the closest-tolerance machine required a larger clearance for the machining head. Direct contact might have alerted either party to question the context further.

5.4.3 Final framework format

Even with five separate tables, the addition of further notes made the table format unwieldy. The notes were therefore removed from the tables and replaced with crosses to indicate each filled cell. Full details of each factor, together with any references and examples, were then set out in sections beneath the table and cross-referred to the cell. This final format is used for the presentation of results in Chapter 6.

5.4.4 Review for completeness and saturation

The framework was reviewed for completeness in that all factors could be accommodated. There was at least one completed cell in each row. Although it was possible for all five cells to be completed, in many cases there was only one factor to relate that reason to one of the sources. The author did not seek to force a relationship where none had been found, although a suggested relationship would be entered as a 'marker' if this appeared appropriate – often this would be supported by an example found later. Because one of the functions of this framework was to indicate likely relationships that may later be built on by others, these markers were left in place.

The factors entered were checked for duplication and saturation. The research notes from the Best Practice study (BPS), the rest of the AEROEXTN Project (AXP), the civil aerospace studies (CAS) and the literature, were reviewed to see where they could enhance the entries by providing additional examples and references to broaden the relationships. It was recognised that the BPS, the AXP and the CAS, had already served as the major source of concepts and ideas for developing the framework. Therefore, only minor adjustments and some additional examples resulted from this review.

5.4.5 Summary table

A summary table was prepared to show the total number of relationships identified in each category of reasons (one row for each of the 5 tables) against the 5 categories of sources. This is in Table 6.6 at the end of Chapter 6.

Chapter 6 The Relationship Framework

This chapter presents the Relationship Framework that is the output of this PhD research, covering step 13 of the methodology set out in Chapter 2. It presents the answers to the research question as a set of five tables relating the possible reasons for manufacturing problems reaching the shopfloor to the sources of information and influence that may cause or prevent them.

Because these results are central to the thesis, they have been included in the main text rather than being relegated to appendices. Many of the references quoted to define the problems or provide examples were not included in the main literature review in Chapter 4, so as to avoid duplicating points of detail.

Each cross in the tables below shows where a specific factor was identified that shows how the type of reason for problems in a row might be related to one of the sources of information or influence in a column heading. The nature of this factor is then set out in the sections that follow. Selected examples are amplified by references to particular literature, or to industrial experience from the AEROEXTN project (AXP), the 'best practice' study (BPS), or the civil aerospace studies (CAS). Where specific issues from Tables 7.1, B.1 or D1-3 illustrate a factor, the reference to the serial number is included, with the prefix S for stainless steel SESAME parts, A for aluminium Parts A, T for titanium Parts T, and C for composite Parts C.

A summary table at the end of this chapter shows the overall number of factors in each category in each column.

6.1 Human-Error

Table 6.1 Human error problems related to sources of information and influence

a	TYPE of REASON for PROBLEMS b	Training and Experience c	Standards Specifications Reports Textbooks d	CAD Systems e	DFM Databases and Tools f	Communication and Teamworking g
1	Wrong advice given to designer	x	x			x
2	Wrong advice given to manufacturer	x	x			x
3	Design's error in constructing CAD model/drawings	x		x		
4	Manufacturing's error in reading CAD model/drawings	x		x		x
5	Wrong information entered into CNC tape generation programme	x		x		x
6	Machine operator error	x				x

6.1.1 Wrong advice given to designer

Reason stated that errors arise from informational problems. They are best tackled by improving the available information – either in the person's head or in the workplace (Reason 1997) p 153. **Factor 1c** is the mistake, based on lack of appreciation of problems or over-simplification, which can be related to the training and experience both of those who seek advice and of those who give it. For example, an inexperienced person might confidently state that there would be no problems with a particular process, when they had failed to look closely at the requirement and had not recognised that the part was impossible to make with the existing machinery. A more experienced person would have known what to look for; a more experienced questioner might have probed more deeply, knowing that the design might be beyond the process limits.

Dimancescu and Dwenger quote Einstein: "things should be made a simple as possible but not simpler" (Dimancescu and Dwenger 1996) p 194. Klein warns against 'ideal' or 'Utopian' solutions, which can only be sustained at the expense of some relevant data. This can cause two things to happen: first it creates the next generation of problems, so that those problems are solved at the expense of the data previously included; second, the idea gets to be defended in ever more fundamentalist and intolerant ways. The idea may then get killed off, with the risk of losing a potentially valuable solution (Klein 1994).

Factor 1d is that of errors caused by the complexity and variety of standards, specifications and products. Ehrlenspiel contends that increases in the complexity of products and processes lead to correspondingly more errors and additional work (Ehrlenspiel 1997) p 482.

Factor 1g is the failure to obtain the context. For example, a production engineer might correctly answer questions on precision capability, but fail to point out that the closest-tolerance machine required a larger clearance for the machining head. Direct contact might have alerted either party to question the context further. Dimancescu and Dwenger benchmarked Japanese methods of communication in NPD, and emphasised the importance of direct contact to discourage loss of meanings that would otherwise occur if information travelled up and down formal channels (Dimancescu and Dwenger 1996) p 53.

6.1.2 Wrong advice given to manufacturer

Factors 2c and 2d are similar to 1c and 2d. Mistakes may be based on incorrect, outdated or wrongly selected information. Again, these can be related to training and experience and the complexity of standards etc. The civil aerospace study contained examples of wrongly selected information, from a look-up table specifying bearing tolerances and from material specification numbers (CAS A3, T6, C11).

Factor 2g covers the failure to convey design intent, or to warn of known problems with similar processes or materials on prototypes or on other projects, so that the manufacturer does not correctly anticipate the difficulties to be faced in production.

Wheelwright and Clark detail the case of a manufacturer who was unable to produce shafts to the roundness required using the specified fixturing, until the designer discovered that the subcontractor that had produced the prototypes had used a modified fixturing. The prototype shop operator had recognised that the fixturing specified by the designer would never have met the roundness standard required, and changed it as a matter of good engineering practice, but had never reported the change (Wheelwright and Clark 1992) pp 290-292.

6.1.3 Design's error in constructing CAD model/drawings

Factor 3c is the lack of training or experience to avoid errors or omissions when building CAD models or preparing drawings. Wheelwright and Clark pointed out that many engineering changes and much expensive time is wasted due not to lack of knowledge of constraints or capabilities, but simply to outright mistakes – e.g. errors in copying figures or sending a document to the wrong location can be costly and time-consuming to correct if not caught early, are often very difficult to track down once they have been propagated in the system, and erode the mutual respect needed for groups to work as peers (Wheelwright and Clark 1992) p 180. The civil aerospace in-house study reported numerous errors on drawings that had previously been used by external suppliers to manufacture parts accepted for aircraft use. Any clarification, corrections, concessions or work-arounds that had been used by the suppliers to overcome these errors had not (for whatever reason) been fed back and the necessary drawing changes made (CAS A3). A simple design error in placing a radius resulted in scrap when it was found on assembly that an outsourced part would not fit (CAS T7).

This may be compounded by **factor 3e**, where a CAD system or drawing protocol is not easy to use, and may be difficult to check or verify. Such problems were evident from the best practice study, where industrial practitioners advised that design offices or consultants that used multiple types of CAD Systems were likely to suffer from the 'use it or lose it' problem of increased errors or suboptimal models when designers were working with a seldom-used system (BPS). In the civil aerospace study, in-house Manufacturing had many queries on drawings that had been prepared some years earlier using a 2D CAD System (CAS A3). The error that led to a part (referred to in the paragraph above) being scrapped was not picked up by Design because it was a late requirement that had not been subjected to the clash detection routine. Arguably, if the clash detection had been readily available for the CAD draughtsman to apply, this mistake would have been detected before the manufacturing instructions were released (CAS T7).

6.1.4 Manufacturing's error in reading CAD model/drawings

Just as the designer may have difficulty in generating a satisfactory representation of the part, **factor 4c** is the manufacturer's lack of training or experience in interpreting models and drawings. This is related to **factor 4e**, where the designer's CAD system produces models or drawings that are difficult to interpret. Where such a poor medium for representation exists, **factor 4g** is the lack of contact to help or explain the interpretation (BPS and CAS). The best practice study also found that a supplier might need the capability to assess older designs that were not in model format. The ability to read and understand drawings efficiently was seen as very important, especially in an industry where new working practices can be adopted on old designs for the purpose of cost minimisation (BPS).

6.1.5 Wrong information entered into CNC tape generation programme

Factor 5c is the lack of training or experience in tape generation, including the failure to appreciate constraints. For example, McMahon and Browne describe the computation of offsets to compensate for the tool nose radius as being "tedious and a source of error" (McMahon and Browne 1993) p 305.

Factor 5e covers errors arising from difficulties in translating models or drawings between the CAD software and the tape generation software – here integrated systems may go a long way towards reducing errors, but may not be practicable where a manufacturer works with several design offices (BPS). Further aspects of format/translation problems are covered in Section 6.5.10.

As with 4g, **factor 5g** is the lack of contact to help match or interpret the design model for tape generation (BPS and CAS).

6.1.6 Machine operator error

Factor 6c is the Operator's lack of training or experience on the equipment and/or working with the specified materials. Peklenik observed the stochastic behaviour of objects being machined as an essential characteristic of the complexity, resulting from various internal as well as external sources of random nature. He cited grinding tool wear as an example of a very complex process which included random breakage of grains, softening of the grain tips and the formation of grain flatness. The wear process was considered as an internal secondary source of disturbances, of the type that could suddenly trigger major perturbations that may lead to catastrophic events such as burning or tool breakage. The training and experience for machine operators was of high importance in avoiding such problems (Peklenik 1999) p 38.

These problems may be reduced by improving the robustness of the design using methods such as the stochastic simulations described by Kazmer and Roser. Their goal was to enable the designer to understand and account for not only the negative effects of manufacturing variation, but also the positive impact of manufacturing flexibility wherein instantaneous corrections in the manufacturing process could frequently improve the product quality and eliminate flaws in the product design (Kazmer and Roser 1999).

Deming states that an operator has completed the learning of a particular job when that person has brought their work to the state of statistical control, whether they were trained well or badly. It is not economical to try to provide further training of the same kind. They may nevertheless, with good training, learn very well some other kind of job. Conversely, if a person's work has not yet reached statistical control, further training will help them. If, however, there is a state of chaos (poor supervision, bad management, nothing in statistical control) it is impossible for anyone in the organisation to develop his or her potential ability and capacity for uniformity of quality (Deming 1986) p 249.

Reason points out some of the consequences of taking advantage of the capabilities of computers to reduce operator errors by automating production processes as much as possible. He quotes the engineering psychologist Lisanne Bainbridge (1987) "The ironies of automation" (Reason 1997) p 42:

- By taking away the easy parts of the human operator's task, automation can make the difficult parts of the job even more difficult.
- Many systems designers regard human beings is unreliable and inefficient, yet they still leave people to cope with those tasks that the designer could not think how to automate – most especially, the job of restoring the system to assay state after some unforeseen failure.
- In highly automated systems, the task of the human operator is to monitor the system to ensure that the 'automatics' are working as they should. But it is well known that even the best-motivated people have trouble maintaining vigilance for long periods of time. They are thus ill suited to watch out for these very rare abnormal conditions.
- Skills need to be practised continuously in order to preserve them. An automatic system that fails only very occasionally denies the human operator the opportunity to practise the skills that will be called upon in an emergency. Thus, operators can become deskilled in just those abilities that justify their marginalised existence.
- And, as Bainbridge pointed out, "perhaps the final irony is that it is the most successful automated systems with a rare need for manual intervention which may need the greatest investment in operator training".

Adler points out that the knowledge intensity of new technologies dictates a greater problem-solving component to operators' jobs than traditional Taylorist approaches would suggest. With automation, the number of operators per unit output might fall, but there is typically no net reduction in average operator skill requirements; on the contrary, higher skills of a new type are usually called for. Training, organisation, remuneration, etc, will need to evolve to reflect this change. Conversely, if the operator is modelled as a problem solver, rather than an effort-supplier, machine design may have to be adjusted to reflect these new tasks (Adler 1989) p 92.

Factor 6g occurs where designers do not receive feedback on problems and 'work-arounds' from previous jobs, and hence fail to avoid features requiring error-prone activities. Further aspects of feedback problems are covered in Sections 6.4.9 and 6.4.10.

When seeking to reduce errors, it is helpful to consider the performance level of the activity being undertaken. Reason (Reason 1990) relates errors to Rasmussen's three 'skill-rule-knowledge' levels (Rasmussen and Jensen 1974). These distinctions of performance correspond to decreasing levels of familiarity with the environment or task.

- Errors at the **skill-based** level are related to the intrinsic variability of force, space or time co-ordination.
- The **rule-based** level is applicable to tackling familiar problems in which solutions are governed by stored rules of the type 'if (state) then (diagnosis)' or 'if (state) then (remedial action)'. Here, errors are typically associated with the misclassification of situations leading to the application of the wrong rule or with the incorrect recall of procedures.

- Novel situations come into play at the **knowledge-based** level, for which actions must be planned on-line, using conscious analytical processes and stored knowledge. Errors at this level arise from resource limitations and incomplete or incorrect knowledge.

6.2 Culture and Social Factors

Table 6.2 Culture/social problems related to sources of information and influence

	TYPE of REASON for PROBLEMS	Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking
a	b	c	d	e	f	g
1	Lack of teamwork					x
2	Rejection of good advice: Disagree on technical grounds	x	x			x
3	Rejection of good advice: Disagree on economic grounds (not cost-effective)				x	x
4	Rejection of good advice: Insufficient time/resources to make change					x
5	Rejection of good advice: Cannot be bothered with minor changes			x		x
6	Rejection of good advice: Unwilling to carry out test programme to prove new/modified process					x
7	Prejudice in Design					x
8	Prejudice in Manufacturing					x
9	Personal antagonism					x
10	Failure to obtain best advice					x

6.2.1 Lack of teamwork

Factor 1g is the need for leadership and the setting of team goals. Leadership is the subject of no fewer than three out of Deming's 14 principles of good management (Deming 1986) p 23.

Thamhain describes it as a myth that the assembly of talented and committed individuals automatically results in synergy and renders such a team impervious to many of the barriers commonly found in the project team environment. High team performance involved four primary factors: managerial leadership; job content; personal goals and objectives; and work environment and organisational support. Management insight had been gained from studies that showed the 12 most significant work-environment factors to be: professionally interesting and stimulating work; recognition of accomplishment; clear project objectives and directions; sufficient resources; experienced management personnel; proper technical direction and leadership; mutual trust, respect, low conflict; qualified project team personnel; involved, supportive upper management; professional growth potential; job security; and stable goals and priorities (Thamhain 1998) pp 2091-2.

Francis describes a supportive team as one that thrives on respecting differences between people. He defines ten different distinct roles of team members from which a balanced team may be constructed, after Meredith Belbin, Richard Boyatzis and Charles Margerison (Francis 1987) p 130:

1. Process manager – channels resources, good chairman.
2. Concept developer – transforms ideas into practical proposals, thrives on complex problems, and enjoys challenges.
3. Radical – sees new possibilities, unconventional approach, generates insight, refuses traditional wisdom.
4. Harmoniser – builds morale, supports, encourages, understands, sociable, promotes commitment and co-operation.
5. Technical expert – specialist contribution, represents expertise, provides informed opinion.
6. Output driver – ensures jobs get done, sets targets, delivers products, completes actions, strong commitment to quality, responsive to time limits, may be autocratic.
7. Critic – stands back, judges, considers possibilities, looks for possible pitfalls, sounds caution, questions proposals, judges ideas; sceptical, decisive, accurate, stable contributors – objective.
8. Co-operator – diligent observer, actively assists team, adaptable, generous, enthusiastic, lacks concern for protocol, broad capabilities, and co-operative.
9. Politician – shapes schemes and collective viewpoints by being opinionated, results-orientated, high in influence, building allowances, guiding others being power conscious and persuasive; confident they know the right thing to do, deliberately try to influence other people.
10. Promoter – links team to others by being outgoing, sociable, building relationships, investigating resources, sensing out ideas and possibilities; 'fixer'.

Francis goes on to describe how transactional analysis (after Eric Berne) can give useful insights into team relationships. Three basic ego states are defined:

- 'Parent' is authoritarian, critical and harsh, but may also nurture others. Strong defence of tradition, unwillingness to consider fresh ideas, and creativity is stifled – subordinates feel judged and they 'close-up'; the truth is often kept from the boss.
- 'Adult' is logical and rational, collects facts, weighs opinions, relates ideas, and comes to reasonable conclusions – invaluable to supportive teamwork.
- 'Child' is spontaneous, joyful, sad, frustrated, demanding, angry or loving – children communicate feelings in an instant, learn to manipulate people and situations to suit their needs, but are made to comply (often rebelliously) with

> the directives of others. The destructive and manipulative side of the child ego states is hazardous in several ways – people become excessively excited and over-optimistic, irrationally distressed or disheartened, actions are taken impulsively, data are ignored, difficulties are taken personally, and debates degenerate into childish arguments.

Francis provides a case example of how the executive in charge of a construction project would adopt the critical 'parent' ego state when anything went wrong. Members of his team hid from him the serious technical problems that were found, because they were frightened to expose themselves to ridicule and humiliation: they reacted from their 'child' ego state.

Such psychological games are subtle but powerful ways for team members to maintain their own integrity through defence or attack. Much behaviour takes place below the level of consciousness, but the resulting communication blockages destroy the possibility of mutual support and can be immensely expensive and time wasting.

There are only two remedies with a chance of success: first, it helps for teams to learn to recognise games; secondly, team leaders can set the tone by demonstrating that "the way to get on around here is to play it straight". These measures can help develop and maintain 'adult' attitudes. Supportive teams develop their capability under good leadership, but are often helped by a deliberate team building process that hastens the development of respect for difference and promotes honest dealing (Francis 1987) pp 130-140.

Golzen reports on a number of aspects of teamworking (Golzen 2000):

- While they can provide a dynamic meeting place for sharing ideas and expertise, they can take up so much time that managers cannot get on with core tasks.
- Forming teams and having meetings must not be an end in itself, irrespective of purpose. There is also the danger of a hidden agenda to prolong the life of the team. People feel the need to belong, and team membership can provide a psychological prop in fragmented organisations.
- Clarity of purpose and goals are more important than the composition of the team and the classification of the roles to be played by members, especially in the case of virtual teams, operating globally and communicating via the Internet. Such teams do not have the benefit of the regular face-to-face communication that is so essential to getting a task done, but they are effective in setting common objectives and highlighting cultural or procedural barriers that may hinder implementation.
- Different tasks also need different kinds of teams. Boats offer a good analogy: members of a rowing crew have a task requiring everyone to be going in the same direction, while people crewing a yacht have different roles, but a common objective.
- In a lot of situations a small task force would be much more effective than a team.

These teamworking factors are involved in many of the issues raised elsewhere in this thesis.

6.2.2 Rejection of good advice: Disagree on technical grounds

The term 'good advice' used in this and the following sections refers to advice that would – perhaps with hindsight – have led to improved part producibility.

Factor 2c is the strong adverse influence exerted by the experience of previous poor performance on the willingness of individuals to adopt new methods.

Miller and Morris contend that the difference between the acceptance of and resistance to change can be framed in terms of expectations for the future. Those who believe that success in the future will be a logical extrapolation of the trends of the past and present may resist innovations and the changes they bring. On the other hand, those who recognise that the only way to achieve or sustain success is through innovation understand that this will necessarily bring change, and they are psychologically prepared to accept it, or even to welcome it. Here the critical aspects are nearly always at the tacit level, as those who resist change may have been strongly influenced by negative experiences in the past that have never been fully analysed and discussed. As long as they remain tacit, they will exert tremendous power even as they are inaccessible and perhaps dangerously obsolete. In the decision-making process, knowledge leads to decisions, which lead to action. The challenge in this process is to make explicit the decision-making models that serve as filters so that they can be evaluated and perhaps revised in the light of new knowledge.

Because of the enormous complexity of dynamic sociotechnical systems, people have false expectations about the usability of information, about the difficulty of translating information to knowledge and knowledge to action. As results, people tend to wait for clarity of information, but with the achievement of full clarity, opportunity is gone. To overcome this tendency, stochastic models of information such as those using the forecasting and scenario-based planning are needed. These tools are used in conjunction with capability development activities in the form of training and practice in individual and group decision-making, with the emphasis on situations characterized by fuzzy options. Sports practice and military war games are examples of necessary investments in developing 'situated' tacit knowledge linked to particular activities and environments (Miller and Morris 1999) pp 195-201.

Maccoby emphasises the need to upgrade leadership and team membership skills and recommends training in brainstorming, listening, asking clarifying questions, and seeking consensus (Maccoby 1999).

Factor 2d is that published material may contain conflicting standards or reports, and further work may be necessary to identify the correct information.

Factor 2g occurs where insufficient expertise exists within the team, and there may be a need to call in additional specialist. This factor may be worse where there should be disagreement with a proposed scheme that is unwise or impracticable, but 'group think' has prevented objections being raised. Several authors describe the effects of group think, a term coined by Janis in 1971 (Janis 1972), and the need for having a team made up of divergent individuals to avoid the effect, e.g. (Reason 1997) p 217; (Hargie, Dickson et al. 1999) p 56; and (Thamhain 1998) p 2092.

6.2.3 Rejection of good advice: Disagree on economic grounds (not cost-effective)

The assessment of cost effectiveness, as used for decision support, depends on what factors are taken into account and how they are assessed. Costing tools that are part of a DFM package may not provide the complete picture (**factor 3f**). Also, the value of developing a new method may lie in its application to future projects (**factor 3g**), so that the team may need to engage a champion to support it. This applied particularly to the adoption of CE, where the current project might not expect to save cost, but would act as a pilot for sorting out the problems and benefit future projects (BPS).

In the civil aerospace in-house study, Manufacturing had requested 3-D modelling for the parts they had been asked to make from 2D drawings. This had been rejected on grounds of cost, partly because external suppliers had previously made the parts and no significant problems were anticipated. With hindsight, it became apparent that some aspects of geometry relating to the proposed 5-axis machining could not been conveyed by the 2D drawings; this aspect, together with a number of errors and omissions that would have been shown up by 3-D modelling, cost significantly more in queries, scrap, rework, and concessions than it would have cost for the 3-D modelling (CAS A2).

A further aspect is the reluctance of designers to initiate changes that compromise performance, for example where the 'ideal' shape would not allow the use of a high-speed cutting tool without leaving excess material that would add weight to the part. This has two important effects: first, it may require considerable effort in meetings or other communications to negotiate the trade-off between manufacturing cost and performance; second, the resulting delay in deciding to make such changes may add to the total design and tooling effort and extend the project timescale. See also Section 6.5.12 g (CAS A2, 4, 5; T1-4; C1, 2, 5, 6, 7, 9, 10).

6.2.4 Rejection of good advice: Insufficient time/resources to make change

Factor 4g occurs where there was insufficient communication to identify the need for change at a stage when it would have involved minimal effort. Prasad asserts that most trade-off studies at the initial stages of the design cycle are done quickly with crude early product data and hence many important analysis steps cannot be performed. When enough design checks are ignored due to lack of time, it is likely that the design, when passed on for downstream operations, may remain unchecked or incomplete. It is much more cost-effective to carry out more iterations and trade-offs during an early part of the design cycle than later (Prasad 1997) p 371. Prasad also recognises the difficulties of dealing with incompleteness and ambiguity – such as having to decide whether to use an approximate analysis early, or to wait until information is complete (Prasad 1996) p 415.

Wheelwright and Clark point out that support groups not directly involved in detailed engineering often find themselves with substantial new responsibilities, but no new resources to carry them out. Restructuring of tasks may be necessary to give support organisations the time and energy to participate in the crucial up-front work that will make their work more effective later on (Wheelwright and Clark 1992) p 334.

6.2.5 Rejection of good advice: Cannot be bothered with minor changes

If a minor change to ease manufacture is identified, it may be resisted by Design if the CAD software is configured so that it involves considerable rework, especially for features entered early in the model build-up sequence (**factor 5e**).

Factor 5g is the failure to make changes to the design that could avoid repeating problems later with design reuse. Busby points out that designs will often not be changed when bugs were found in them: either because downstream functions (like Manufacturing) had fixed the bugs and not informed the designer, or because the designer was reluctant to spend effort in changing the original design and re-issuing it through a cumbersome change procedure (Busby 1997) p107. The importance of making even minor changes for ease of manufacture should not be underestimated in its effect on Manufacturing morale and the promotion of teamwork.

Wheelwright and Clark's example quoted in Section 6.1.2g of a prototype shop failing to communicate a necessary change of fixturing is equally applicable here.

The effect of not bothering to communicate minor changes and workarounds is amplified when there is a change of manufacturer. In the civil aerospace studies, the in-house manufacture of a part that had been produced previously by more than one supplier revealed a number of queries on the supposedly mature drawings (CAS A3).

6.2.6 Rejection of good advice: Unwilling to carry out test programme to prove new/modified process

Factor 6g is when there is no risk assessment for a process that is not already familiar to both Design and Manufacturing, or the assessment fails to identify and accept the need for testing.

The best practice study contained examples of suppliers who were keen to expand their capability. However, major customers had experience of unfulfilled promises from overoptimistic suppliers, and urged caution when adopting untried sources (BPS).

6.2.7 Prejudice in Design

Factor 7g occurs when Design are prejudiced against the views and expertise of other disciplines. For example, they may not appreciate the value of employing the expertise of Manufacturing. Francis describes the phenomenon of 'prejudice' as a set of attitudes that predisposes a person to think well or badly of an identifiable group, based on logically invalid generalisations, which cannot be supported objectively. Prejudice occurs when one group believes that another is inferior, and is so deeply ingrained that we must expect to see it in organisations. Because it undermines co-operation, provokes conflict and inhibits genuine communication, prejudice is an important consideration for managers (Francis 1987) p117.

One of the barriers to teamworking is the tendency to stereotype and devalue 'other' views (Thamhain 1998) p 2091. 'Class distinction' between Design and Manufacturing engineers must be overcome.

Liker and Fleischer suggested that conscious team-building exercises could help uncover differences in functional perspectives and help members constructively use these differences to encourage creativity (Liker and Fleischer 1992).

Ashkenas states that intense socialising experiences go a long way toward removing barriers between people and breaking down stereotypes (Ashkenas, Ulrich et al. 1995) page 301.

Durand and Crémadez explain how a major deficiency in attitudes can destroy the whole ability to innovate of an otherwise efficient company. Transforming the culture of the organisation in order to generate new attitudes, more compatible with the specific needs of innovation, in turn means *unlearning part of the existing cultural base.* To generate new learning and some form of unlearning in a context where the pre-existing competence base tends to deny and reject new representations, one way may be to organise the contextual conditions which would make it possible for entrenched routines to appear insufficient. A key element is then to make sure that the new context does not render the previous representations and routines fully obsolete, but only partially unfit to cope to the new challenges. The former and the new representations, as well as the former routines (operations orientated) and the new processes (innovation focused) have to operate simultaneously, if not harmoniously. The challenge for management is to design the new processes in such a way that the individuals can cope with the rhythm, the timescale, the pressure of both the normal operations and the newly required innovative processes. One of the best triggers may be to use some external force, suddenly presented as a major threat to the firm. Creating a feeling of urgency may thus be used as a *catalytic shock* to the organisation (Durand and Crémadez 1999) p 361.

6.2.8 Prejudice in Manufacturing

Factor 8g is that Manufacturing must be able to see that their advice is respected and responded to, even where it cannot be adopted. If not, there will be a communication problem because they will stop offering suggestions if they feel ignored.

Thamhain highlights the possibility of lower-status individuals being ignored, thus eliminating a potentially valuable resource. While some struggle for power is inevitable in a diverse group, it must be managed to minimise potentially destructive consequences (Thamhain 1998) p 2091.

Ettlie states that a critical and still unresolved problem is the issue of availability of qualified, well educated, professionals, capable of claiming equal status with other team members and well experienced manufacturing personnel that can be taken away from operations responsibilities (Ettlie 1995) p 108.

Wheelwright and Clark regard the management of distrust as crucial. Actions to break down barriers of distrust may include transferring people across boundaries, establishing working teams so that people can build up relationships that will support trust, and taking extraordinary measures to encourage individual creativity (Wheelwright and Clark 1992) p 334.

Todd explains how attitude problems, when people persistently fail to give the commitment and co-operation expected by management, will often have their roots in fear, but there can be other causes that need to be recognised and tackled. The three most commonly found are resentment of criticism because "I know best how to do my job"; a deep-rooted commitment to traditional priorities, so that overcoming today's problems always takes precedence over efforts to improve future performance; and a feeling that any improvements achieved will primarily benefit 'management' – often expressed as "What's in it for us?" (Todd 1995) p110. This aspect is strongly related to both Teamworking (Section 6.5.1) and Metrics and Rewards (6.7.8).

6.2.9 Personal antagonism

Factor 9g is where antipathy between individuals can compromise performance. Team leaders or facilitators must recognise any such problem and take steps to overcome it.

Maslow states the general assumption that people get more pleasure out of loving than they will out of hating, but warns that the pleasures of hating are real and should not be overlooked. For fairly well developed people, the pleasures of loving, friendship, and teamwork, of being part of a well-functioning organisation are real and strong – and greater than the pleasures of disruption, destruction, antagonism etc. However, for people who are not highly developed, i.e. for deeply neurotic or psychotic people, there is the fair number of instances in which the pleasures of hatred and destruction are greater than the pleasures of friendship and affection (Maslow, Stephens et al.1998) p 20.

6.2.10 Failure to obtain best advice

The people best placed to advise should be included in the team, or brought in to advise. **Factor 10g** occurs when a prime specialist was absent from the discussion or represented by a deputy – team leaders or facilitators must recognise the importance of following up topics for completeness and balance in such circumstances. A team member's absence may be related to conflicting priorities, which may in turn reflect the attitude and commitment of the individual. Todd warns of the need to anticipate and manage this problem, for example by emphasising senior management commitment, setting time management targets, monitoring achievement and setting a good example (Todd 1995) p 110.

Conley reported the case where, as a result of their regular absences from development meetings, the marketing function was unaware that year one production of an innovative product was to be limited to only 30,000 units. Tooling was not designed to handle marketing's projected volumes of 100,000+ engines in year one, so that sales orders could not be satisfied. The resulting difficulties disappointed many members of the core team, and most of them eventually left the company. The considerable know-how acquired during the development program left with the core team members (Conley 1998).

6.3 Knowledge

Table 6.3: Knowledge problems related to sources of information and influence

	TYPE of REASON for PROBLEMS	Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking
a	B	c	d	e	f	g
1	Lack of Know-how	x	x	x	x	x
2	Lack of knowledge of manufacturing processes	x	x		x	x
3	Lack of knowledge of material behaviour during processing	x	x		x	x
4	Failure to recognise that advice is needed	x				x

6.3.1 Lack of Know-how

Factor 1c is the lack of know-how that can be improved by training and experience, which covers CE principles as well as people's own specialisation. The following points should be considered:

- In a joint study with industry, Beitz and Helbig reviewed the future education of product developers and found "massive deficiencies in the fields of non-technical basic knowledge, methods- and system-competence as well as in the social competence." In contrast, they found deficiencies in fundamental technical knowledge to be very small. (Beitz and Helbig 1997). However, Ashkenas pointed out that if employees want to act and are trained to act but then are not allowed to act – to make decisions with good information – they are highly likely to become frustrated (Ashkenas, Ulrich et al. 1995) page 51.
- Much knowledge is tacit and needs to be learned through experience. Narasimhan contends that commonsense behaviour is essentially underpinned by tacit knowledge (Narasimhan 1997).
- Professor Ghoshal of the London Business School is reported (Dearlove 2000) as stressing the importance of addressing human capital at a more profound level than that of creating an internal market for knowledge: "Often we make the mistake of thinking of human capital as just knowledge. A second important aspect is social capital - networks and relationships. The third dimension is emotional capital - the ability and willingness to act. There is no solution other than a trust-based culture. It's not so much a case of "I have this knowledge which I give to you," it's more how you shape questioning and frame learning. At BP, for example, a quarter of the knowledge management budget is spent on coaching people."
- People need to be coached into asking the right questions so as to share knowledge. Marsh pointed out that designers needed to be confident of the validity of their question before placing trust in the answer obtained. The

questions asked, or information sought, frequently did not represent the knowledge ultimately required (Marsh 1997) p 109.

- Ehrlenspiel regards one of the consequences of the knowledge-explosion as an increase in the barriers of communication between specialists, because new 'interface problems' are arising as new technical terminologies are developed, which are not understandable by others. So, in spite of knowledge-explosion, lack of knowledge for the product-development may cause time-consuming modifications (Ehrlenspiel 1997) p 482.

The sharing of education and training may help to integrate suppliers into the new product development process. In a study of the management practices of 60 companies, Ragatz et al cited this management factor as a significant differentiator between the most and least successful efforts (Ragatz, Handfield et al. 1997).

Factor 1d is the need to appreciate the range, scope and currency of published information available, and the importance of knowing where to look.

McMahon stressed the vital importance of the way information is processed when it comes into an organisation – e.g. supplier information, standards, journals, customer feedback and so on. Strategies for information filtering, indexing and management should be in place. Rapid connection to information will be enhanced by encouraging design staff to develop specialisms for which they collate and publish information, and by maintaining directories of specialist expertise. Experience can often be organised in the context of the incremental development of established design concepts. Organisations should adopt formal strategies for the organisation of information about precedent designs – such as QFD and FMEA charts, in-service records, 'best-practice' and 'lessons-learned' databases and so on (McMahon, Lowe et al. 1999).

Factor 1e covers shortcomings caused by the complexity of CAD Systems. Full-featured CAD system training is expensive, and is not normally given to those needing only occasional access to models. CAD skills learned can be lost if not regularly applied. Major customers often require component models from their suppliers in their own CAD system and software revision level. Suppliers may have difficulty in maintaining their proficiency in working with several different CAD systems (BPS).

Factor 1f is the lack of understanding of the context, capability and limitations of DFM tools and software. Lack of familiarity may discourage or limit its use (BPS).

Factor 1g results from of lack of knowledge of communication and meetings skills, and the need to gain confidence in communications media and working as a team player. Ehrlenspiel et al studied the way design students worked in teams, and found that most of the disadvantages of teamwork in design occurred because of problems of communication between the team members (Ehrlenspiel, Giapoulis et al. 1997). Communication media requiring extensive training may discourage participation.

6.3.2 Lack of knowledge of manufacturing processes

Factor 2c is the need for training of engineering designers to include the characteristics of different manufacturing processes to avoid the problem of DFM mismatches. Peklenik emphasises the role of education and training in giving an individual the chance of getting relevant knowledge and experience. For the human operator to control the manufacturing activity, he must possess several abilities, enabling him to do these jobs with competence, reliability and with the sense of responsibility. The subject must: understand the organisational structure of the workstation, the operations involved in the manufacture of the specified output, and the art of control of the workstation in order to accomplish set of objectives; have the ability to trust, to communicate, to share the knowledge, and to work in a team; be able to adapt quickly to unpredictable situations (Peklenik 1999) p 38.

In the AEROEXTN Project there were three examples of issues that the designer might have been expected to avoid by applying 'textbook' producibility principles: a geometry mismatch likely to leave machining marks on an adjacent face; a rectangular slot that could have been specified with semicircular ends for easy machining; and holes to be drilled at an angle to the surface, which would be awkward to machine without spot faces (AXP S1, S5 and S9).

In the civil aerospace studies it was found that overstretched design departments were reluctant to release people for updating training or to attend seminars and conferences unless these were deemed essential. In particular, it was unusual for contract hire staff to be released for what might be regarded as general career development (CAS).

To avoid the selection of sub-optimal company standards or processes (**factor 2d**), publications should reflect all currently available methods (BPS). In the civil aerospace study, Design reported that the company Design Handbook for composite materials was in course of preparation. The designer responsible for composite panels stated that he would have been prepared to accept a 'wish list' from the supplier (based on their experience from manufacturing panels for earlier aircraft). This might well have reduced the need for some of the producibility interactions, especially those regarded by Design as being supplier site-specific (CAS C2, 3, 5, 6, 9 and 10).

Factor 2f is that databases and tools may contain only absolute process limits without guidance on optimum application or alternative processes (AXP).

Factor 2g is where feedback of information on difficulties in manufacture does not reach designers effectively. Busby cites the following (Busby 1997) p107:

- People such as test engineers, manufacturing engineers and installation engineers sometimes had limited diagnostic abilities, and tended to attribute problems to a product's design in the absence of better information.
- Such people also tended to communicate their *diagnoses* to designers, not the *symptoms* – so designers typically had to make corrective decisions with surprisingly poor information.
- People in other functions often categorised problems in different ways from designers.
- Designers' preferred ways of receiving feedback (usually written channels, to avoid interruption and distraction) differed from others' preferred mechanisms for giving feedback (usually verbal, direct and immediate).

The civil aerospace study showed that considerable delay in resolving minor queries could arise for a mature part on the change of manufacturer. The original design team had moved on, and the paper-based works query note (WQN) system received low priority from a design office support team dealing with a range of other matters (CAS A3).

6.3.3 Lack of knowledge of material behaviour during processing

Factor 3c is when new applications of materials and processes have not been tested to reduce the risk of production problems.

During the AEROEXTN project it was noted that engineers from the design team for an earlier missile project had spent considerable time working with the supplier to develop processes on the new 5-axis workstations so as to produce acceptable parts (AXP).

Factor 3d is that effort is wasted and projects are delayed because reports often do not include details of unsuccessful trials, or methods investigated and rejected, as well as successful solutions (AXP & BPS).

Factor 3 f is where databases and tools apply geometrical constraints without regard to 'live' process characteristics (BPS). Brissaud and Tichkiewitch describe the development of design synthesis tools to constrain part definition, and point out the advantage of coupling the design engineer's and the process planner's activities so that (for example) rigidity is considered globally by the rigidity of the part in use and the rigidity of the part while machining (Brissaud and Tichkiewitch 2000) p 118. In the civil aerospace study, one of the composite panels had a greater degree of double curvature than the flatter panels on previous aircraft: the original 'ribbon direction' would not allow the honeycomb insert to conform to the shape correctly. The ribbon direction parameter had not been included in the database (AXP C3).

Factor 3g is the need for advice and feedback between Design, Manufacturing and Tooling (as Busby in 6.3.2g above).

6.3.4 Failure to recognise that advice is needed

Factor 4c is where people do not have the training and experience to recognise the limits of their knowledge. De Bono describes the concept of 'unique rightness' whereby people believe they are right because they cannot imagine any alternative explanation that fits the facts available. It is impossible to exclude an alternative explanation simply because no one can think of one – at the moment. People with feeble imaginations are the most sure of their conclusions. What is only a tentative explanation for lack of a better one can quickly become dogmatic certainty, especially when the idea is taken away from the originator and passed from mind to mind becoming less tentative with each passage. A person may go to great lengths to demolish alternative explanations in order to strengthen their feeling of rightness, even when the little evidence available fits all the alternative explanations equally well (de Bono 1971) pp 118, 123.

Factor 4g is where team members are not familiar and up-to-date with the environment of their fellow members. They should be encouraged to visit each other's workplaces to help them understand the background and circumstances under which designs are developed and parts are made. Designers often are not familiar with the shop floor, or have been away from it for a long time. They may not appreciate the constraints that are obvious when the facilities and work in progress are seen at first hand. Production or Manufacturing, who work with these constraints every day, see them as so obvious that either they do not think to raise the subject, or they regard Design in a poor light for not being aware of them (AXP & BPS).

6.4 Organisation

Table 6.4 Organisation problems related to sources of information and influence

	TYPE of REASON for PROBLEMS	Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking
a	b	c	d	e	f	g
1	Communication: Did not know whom to contact	x				x
2	Communication: Cumbersome/time-consuming procedure					x
3	Communication: Contact not available					x
4	Communication: Contact could not understand problem	x				x
5	Communication: Combination of factors involved required complex interaction between parties to resolve – no forum existed with right level of participation by appropriate specialists to address					x
6	Not cost optimising				x	x
7	Not optimised for process				x	
8	Inappropriate metrics and reward system					x
9	Lack of feedback - no learning from previous projects to avoid problems					x
10	Lack of feedback - no learning from queries and concessions on current work					x
11	Wrong standards, when correct standards available	x	x			x
12	Information not shared by Design for commercial/political/parochial reasons					x
13	Information not shared by Manufacturing for commercial/political/parochial reasons					x
14	Failure to consult/involve suppliers, including third parties (e.g. material suppliers, sub-contractors)	x				x
15	Failure to anticipate problems	x	x		x	x
16	Lack of ability					x
17	Lack of effort					x
18	Lack of time					x

6.4.1 Communication: Did not know whom to contact

Factor 1c is where there is a lack of clear guidance on responsibilities and specialist interests in the organisation. This can be reduced by publishing contact details, establishing focal points, and emphasising their importance in the induction courses for a new employees and staff who move between departments. Backhouse and Brookes reported that, when Rolls-Royce developed a new concurrent engineering process, one of the essential features that differed from previous work practices was the database of contacts at suppliers, to which designers could have direct access. Without rapid access to experts at relevant suppliers, designers would never have time to consider alternative technologies, but would revert to consulting their 'little blue books' of helpful contacts. The essential benefits of the corporate database were: it could ensure that suppliers had acceptable terms of business before they were entered onto the database; 'make or buy' policies could be enforced; and designers could be preferentially directed to the best-performing, commercially-compatible suppliers. Creating and maintaining such a database was not a minor task – data had to be sufficiently detailed to ensure that the appropriate suppliers were registered against the correct component types or manufacturing concepts, and data on contact names, telephone and fax numbers needed to be kept up-to-date (Backhouse and Brookes 1996) p 200.

Factor 1g is where people who need to communicate do not know each other. In a study covering several different industries, Swink et al found that some projects emphasised collocation and face-to-face communication. Others relied on phone conversations, documents, and electronic mail. Projects focusing on design quality relied on formal presentations and periodic review meetings. Projects emphasising development speed required frequent, informal communications. Programs addressing design quality required extended product definition and performance testing, with input from design engineering, marketing, and customers. Efforts to reduce development time involved small, informal teams led by design engineers and managers. Aggressive product cost goals necessitated intensive interaction between product designers and manufacturing personnel. Highly innovative products required early supplier involvement and joint engineering problem solving. Formal design reviews and shared design data systems aided information sharing between internal and external design groups (Swink, Sandvig et al. 1996).

Drucker emphasises that the effectiveness of an information system depends on the willingness and ability to think through carefully what information is needed by whom for what purposes, and then on the systematic creation of communication among the various parties to the system as to the meaning of each specific input and output. The effectiveness depends on the pre-establishment of communication (Drucker 1973) p 489.

6.4.2 Communication: Cumbersome/time-consuming procedure

Factor 2g is where organisations prohibit direct contact, or make it difficult for people who need to discuss complex issues or trade-offs to communicate (e.g. require all queries to be submitted in writing through an intermediary). This may be overcome by developing a management policy that allows direct contact in appropriate cases, and monitors matters to ensure that Design advice is accessible without designers being pestered with trivia (BPS).

6.4.3 Communication: Contact not available

Factor 3g is lack of immediate contact, or deputy prepared to look into the query/problem, that may frustrate the originator. Drisis found that designers looking for information and documents tended to follow the following sequence: they searched their own documents and folders first when they thought they had the information themselves somewhere (this was the least probable case, however); then they spontaneously asked some 'well-known experts' or the colleagues next to them for help; finally, they kept asking until somebody could provide an answer or **until they were bored** (Drisis 1999) p. 568. Clearly, if they got bored before contacting the person with the best answer, their subsequent actions would not be based on the best information.

Crabtree et al report that expertise among more senior people is always in demand at a company. Many of the older employees are veterans of many years, and have stores of knowledge the importance of which even they do not appreciate. When the more junior members need to find out something from the senior people, they very often are inaccessible, due to the amount that they are in demand, and their knowledge therefore does not benefit the others in the way it could. In addition to this, the moment that such an employee walks out the door on retirement, most of their knowledge walks out the door with them. The results of this knowledge may be present at the company in the form of designs, reports, drawings, etc., but the process that generated the work is not recorded, and therefore not retrievable. This information is a tremendous asset of the company's, but the company can no longer benefit from it after the retirement of the employee within whom the knowledge resides (Crabtree, Fox et al. 1997).

Two points arise from this: the importance of capturing information from experienced people before they leave the company; and, where such information has not been captured and been made available to those who need it, making sure that access is granted to those with the knowledge – however senior they may be.

6.4.4 Communication: Contact could not understand problem

Factor 4c is the lack of the ability to understand, which can be reduced by training and improved by experience. Miller explains learning as knowledge brought about by a process of integration of information derived from data, plus theory that puts the information in the proper context, plus experience of how things work on the real world. (Miller and Morris 1999) p 77. Safe environments must be created for positive learning experiences to occur, whose essential elements include (Miller and Morris 1999) p 266:

(1) Opportunities for training and practice;

(2) Support and encouragement to overcome the fear and shame associated with making errors;

(3) Coaching and rewards for efforts in the right direction;

(4) Norms that legitimise the making of errors;

(5) Norms that reward innovative thinking and experimentation.

Factor 4g occurs because people with different perceptions may fail to grasp each other's point of view, however carefully it is explained.

Drucker's emphasis on the need to pre-establish communication for greater effectiveness, referred to in 6.4.1g above, is equally importnt here (Drucker 1973) p 489.

Coleman and Day reported that a survey of industrial designers suggested that the two factors ranked most highly for improving the effectiveness of design decisions relating to manufacturing issues were: to provide more opportunity to see the physical product (considered significant by 57% of respondents) and more opportunity to see manufacturing processes at first hand (47%) (Coleman and Day 1999).

The AEROEXTN Project showed how a low-cost viewer on a PC could enable a supplier to view, use a red line mark-up facility, and comment on a 3D model of the design, readily generated from the main CAD system. This was especially useful where the supplier did not have a compatible CAD workstation, and it could also enable production engineers and shopfloor personnel to see and manipulate the model without formal training and without having to leave their normal workplace (AXP).

6.4.5 Combination of factors involved required complex interaction between parties to resolve – no forum existed with right level of participation by appropriate specialists to address

Factor 5g is where the organisation has not developed their communication and teamworking to match the complexity of the CE task.

Wheelwright and Clark define four modes of communication, appropriate to varying degrees of product development, maturity and time pressure. Where problem solving between upstream and downstream groups is intimately connected, the practice of 'throwing the design (blueprints) over the wall' will not support timely mutual adaptation of product and process design. What is needed to capture the nuance and detail important for joint problem solving is face-to-face discussion, direct observation, interaction with physical prototypes, and computer-based representations.

The essence of mutual adjustment is real-time co-ordination between upstream and downstream engineering groups. In this way design engineers take into account the preliminary results of process engineering problem solving in order to make products easier and less expensive to manufacture (Wheelwright and Clark 1992).

Adler discusses the selection of co-ordination mechanisms, emphasising that the more interactive mechanisms can be very burdensome in meeting time. He gives the example of an explicit set of criteria developed by one company that distinguished four levels for deciding how much interaction a given project would need:

1. Rely on standards, then use manufacturing prototypes to resolve residual fit issues.
2. Conduct a meeting with manufacturing staff early in the design phase to set some general parameters, then rely on the sign-off to ensure that they have been respected.
3. Designate liaison people to conduct occasional in-progress design reviews.
4. Implement a full product-process design team.

However, if the product-process fit issues embody exceptions with respect to prior experience, the organisation would need to plan for some design changes. If the number of exceptions were high, advance planning would not be able to anticipate them, and the manufacturing function would subsequently need to propose fit-enhancing changes. A transition team that brought design engineers into manufacturing could be very useful where the novelty was particularly high. Another aspect of DFM fit uncertainty is analysability – the difficulty of the search for the answer to the given DFM problem. High novelty of DFM fit problems creates the need for more interaction during the given phase, but low analysability forces the project to postpone the resolution of some of those fit problems to later phases, where new information will be created (Adler 1992) pp 146-147.

In a study of 10 high-tech companies Jassawalla and Sashittal concluded that how new-product-related technology transfer and human interactions were managed in high-technology firms remained under-studied. They found managers challenged by the prospects of linking together diverse functional groups that otherwise work separately, of increasing production's and marketing's stake to equal that of R&D's, and of ensuring that the exchange of information added value and resulted in creative new products. The study showed that creating a culture of interdependence, mindfulness and transparency was critical for sponsoring high levels of synergistic NP-related human and interpersonal interactions (Jassawalla and Sashittal 2000) p 49.

6.4.6 Not cost optimising

Factor 6f is that analysis tools may enable designers to see where the costs of manufacture lie for a given model and processes, but will not normally recommend alternative geometry or processes. The designer would then have to devise an alternative scheme for the tool to cost. Minis pointed out that most of the rule-based approaches would require large sets of rules to calculate realistic manufacturability ratings for cases where interactions among manufacturing operations make it difficult to determine the manufacturability of a design directly from the design description (Minis, Herrmann et al. 1999) p 384.

Factor 6g is where designers have not developed teamworking with the other departments to combine their skills in looking for innovative ways to optimise costs and achieve the greatest cost reductions. Todd emphasises the importance of designers combining their skills with the skills of all the other departments involved, to achieve 'better than ever' cost reduction. It is important to recognise that some of the key people involved may feel that their professional ability is being challenged, and their (often unspoken) fears may have to be laid to rest by pointing out that they had not previously had the opportunity to apply their professional skills to the full because of the emphasis previously placed on achieving other goals (Todd 1995) p 257.

6.4.7 Not optimised for process

Factor 7f is that tools that are generic in their application may not be optimised for specific processes. However, where process-specific tools are available, decisions on process may not be made (or may be changed) after significant design work is complete, resulting in a sub-optimal solution. Lempiäinen points out that examples used in training to motivate designers tend to refer mainly to mass production products, and thus show exceptionally good results in terms of lead time and cost savings. However, the case stories can seldom point out how the designer can solve problems in the flexible small batch production environment (Lempiäinen 1997) p 577.

In the AEROEXTN project there had been nothing to prompt the designer to include a tooling hole, which the production engineer considered would significantly improve the manufacturing process. There were no rules to guide the SESAME designer, so that it took three producibility interactions for the appropriate size, placement and tolerances of the tooling hole to be agreed (AXP S3, 8, 12).

6.4.8 Inappropriate metrics and reward system

Factor 8g is that rewards may depend on metrics or criteria that are too narrowly focused, especially where they may actively discourage working for the common good of the organisation.

Wheelwright and Clark emphasise the need for managers to be sensitive to those aspects of their systems that get in the way of the kinds of change that new capabilities require. The process engineer who said "that's not my job" when required to get involved early in the design phase of a product lacks information on the purpose of such involvement and the incentives to undertake it. Indeed, what the engineer means is "... that is not what I get paid for, that is not how I get rewarded, there is nothing in it for me." Individuals need to understand the value awaiting them in working with the new or improved approach. Experience has shown that once product and manufacturing engineers get involved in working together in an integrated fashion, the benefits become apparent. Getting involved can create opportunities for them to substantially improve their performance, the quality of their work, and the performance and quality of others' work. It also influences their quality of life at work (Wheelwright and Clark 1992) p 334.

Deming emphasises the damaging effects of the fear that may result from the way individual performance is assessed and merit is rewarded. He cites the example of a person afraid to contribute their best efforts to a partner or to a team, because their contribution may lead to someone else getting a higher rating than them (Deming 1986) p 60. Deming strongly decries the evaluation of performance for an annual review, or merit rating. He considers that 'management by fear' would be a better name than 'management by objective' or 'management by numbers', because such measures nourish short-term performance, annihilate long-term planning, build fear, demolish teamwork, and nourish rivalry and politics (Deming 1986) p 102.

The challenge for management lies not so much in motivating people as in building an environment where motivated people are willing to make a maximum contribution (Maslow, Stephens et al. 1998) p 68.

Ashkenas et al consider it a myth that the broad sharing of rewards creates healthy hierarchies. People also require competence, information, and appropriate authority to act. They warn that rewards alone often encourage random or even counter-productive behaviour (Ashkenas, Ulrich et al. 1995) p 51.

Lonsdale and Cox (Lonsdale and Cox 1998) p 151quote Burt and Doyle's six principles of the philosophy of measurement:

- There should only be a small number of measures;
- The measures must be straightforward;
- The focus of a measure must have a significant impact on the business;
- Measures must be assigned to a named individual or individuals;
- Measurement report distribution must be agreed and formalised;
- Responses to various levels of performance must be agreed in advance (Burt and Doyle 1993) pp 185-186.

While this provides the broad rules of the measurement challenge, they suggest (Lonsdale and Cox 1998) pp 151-152 the more detailed framework that recognises the importance of innovation provided by Kaplan and Norton's 'balanced scorecard'. This tool involves the four perspectives of: financial; internal business; customer; and innovation and learning. This scorecard brings together many of the seemingly disparate elements of the company's competitive agenda and allows the Board to assess whether improvements in one aspect of the business's performance is causing lower performance elsewhere (Kaplan and Norton 1992) p 71.

Measures frequently address short-term local goals rather than corporate goals: for example, where a designer is tasked with completing a model or drawings by a given date, with no account being taken of the errors, queries and design changes that may result from the work being hurried. In a UK Department of Trade and Industry presentation in 1998, following an American tour by a group of specialists looking at best practice, it was reported that the Chrysler Corporation had moved to a reward system that depended only 50% on performance in the specialist task, while giving the other 50% for communicating with others.

Cooke, McMahon and North suggest a system of metrics for the design process, based on the analysis of design changes during development, that can be used as an aid to improving design quality (Cooke, McMahon et al. 1999).

Cleetus recommends project assessment tools that generate metrics to assist in task co-ordination, perhaps displaying colours on Gantt charts to provide a useful qualitative view for managers. For example, an understandability metric of project tasks might be displayed with green for the perfectly understandable tasks (all outstanding questions satisfactorily answered), yellow for those with of over half the questions answered, and red for those with less than half (Cleetus 1998) p 255.

Teschler reports on the metrics used by a developer of surgical products. Because metrics could grow stale, they regularly convened a special team of group leaders, support partners, and others involved in product development to decide whether the current metrics by which teams got measured still made sense. Corrective action reports, products released, resource allocations, and customer feedback issues had all, at one time or another, been used as process measurements. If teams found better indicators, old ones got jettisoned to make way for new yardsticks of performance. They were moving toward metrics to predict performance rather than to react to problems. They also had to work to get developers past the idea that metrics would be used against them, rather than a tool they could use themselves. One early insight was that it made no sense to apply the same norms to all projects regardless of their complexity. Now, efforts revolving around technological breakthroughs got measured separately from others (Teschler 1999).

Lynn and Reilly claim that a lack of useful metrics is undoubtedly one reason that the success rate of new product development has not improved appreciably over the past 40 years. If companies could measure their innovation process—if they had reliable metrics to gauge their performance—then specific problem areas could be addressed and managers might see the same improvement in their innovation efforts that they have come to expect from their quantifiable TQM programs. The 'Innovation Report Card' was being developed as a new method for measuring new product team performance and comparing that performance to a standard to determine if and where improvement is needed. The most important factors would depend on the goals of the new product team (Lynn and Reilly 2000):

- If the team wants to reach market quickly, they found that having a good NPD Process, a Stable Vision and a Stable Team were particularly important;
- If the team is trying to develop self-correcting, self-directed teams (information implementation) then NPD Process, Team Stability, Management Support, Recording, and Reviewing were critical;
- If the goal is simply successful innovation, then NPD Process, Management Support, Reviewing, and Vision Clarity were crucial.

Kormos reported that most management teams vastly underestimate the time needed to design and implement a strong metrics program. Experts recommend planning on years, not months, to get metrics functioning effectively. One of the least utilized tools was predictive metrics to measure activities or results critical to the major goals, such as whether a project will come out on schedule. Metrics tracked in this regard have included requirement changes, design changes after prototype, and time-to-achieve-full-staffing. All these can help identify problems early. For motivational metrics, Kormos reports Arthur M. Schneiderman's 'half-life metrics' – the time required to achieve 50% reductions in a performance gap. These are aimed at managing the wasted effort and elapsed time spent on error corrections. Making gap reduction an objective during the product development cycle will have immediate and measurable bearing in almost every case on the cost of the project, the cycle time, and the quality of the output delivered to a customer. Teams seeking to make 5x and 10x type improvements must be able to assess root causes and arrive at remedies expeditiously, using structured problem-solving approaches. During the 1980s, NEC delivery teams used the metric of 'Problem anticipation rate' = Number anticipated x 100 % / (Number anticipated + Number not anticipated) for PC software from approximately 25% to almost 100 percent, for microcomputer systems from 10% to over 50%, and for microcomputer modules from just under 60% to about 65% (Kormos 1998).

R.J. Might reported, as one possible measure of project technical success, the ability of the project team to identify technical problems before they reached crisis proportions (Might 1984) p 128.

In contrast to the experience of 'what gets measured gets done', Mariotti cites Hewlett-Packard's 'muddled teams' concept, described in Fortune by Stratford Sherman (1996), as an example of successful efforts that defy measurement in the normal sense. In this instance, by agreeing to levels of improvement previously thought impossible, the HP team leaders 'bought' the freedom to design the new processes through an uncontrolled and near-chaotic team process. When asked how often they reported progress to the corporate management at HP: "Not very often, if we could avoid it. It was very hard to honestly represent the situation in those early days in a way that would mean anything to people from outside the team." (Mariotti 1997) p 259. Pugh highlights the significance of the interaction between types of control and patterns of communication (Pugh 1996) p 508, quoting Might: "Unfortunately for the project manager, the implementation of certain control systems can interact with communication patterns to produce a negative impact on success... If project team members know what has to be done, how difficult it is, and that they will be pressed to get it completed in a satisfactory manner, the added burden of supporting a reporting system on the accomplishments may be too much (Might 1984) p 131."

In a study of how a vehicle manufacturer was measuring the co-development performance of over 300 suppliers, Johnson and Evans found that very few organisations effectively measured their product development capability and that the use of subjective measures was more extensive than objective measures. Industry and academics found product development a hard area for measurement. The amount of time and effort required to pioneer in a 'difficult' area was high, and not knowing if the benefits were less than the input effort could cause practitioners not to bother (Johnson and Evans 1997).

6.4.9 Lack of feedback - no learning from previous projects to avoid problems

Factor 9g occurs when organisations do not provide a mechanism for recording and accessing problems and solutions from previous projects, or for communication between teams. Weber emphasises the importance of effective and sufficient horizontal communication between the Integrated Product Development (IPD) teams to avoid IPD 'silos'. The traditional 'silos' were the design engineers' silo, strength engineers' silo, tool designers' silo, manufacturing engineers' silo, etc: now IPD teams need to avoid the tendency to have IPD 'silos', each silo consisting of a design engineer, a strength engineer, a tool designer, a manufacturing engineer, etc (Weber 1994).

Kormos stresses the importance of knowledge archives, quoting the example of a business equipment manufacturer who captured lessons learned from every project in a structured Lotus Notes database: "Our rule is you're not done until the team has captured what they've learned." (Kormos 1998).

Busby found that there were repeated errors where design organisations had failed to embody past experience in new products. The motivational function of feedback was vitiated by the absence of objective outcome measurements and little systematic guidance to designers on effective behaviours. Designers also believed there was a strong bias towards negative (that is critical and unfavourable) feedback in their day-to-day work. Several of these problems have more general explanations: (1) a general under-estimation of the extent to which knowledge of results contributes to job satisfaction among designers; (2) a similar under-estimation of the extent to which designers are uncertain about the consequences of their decisions and their general performance; and (3) a strong current-task orientation which discourages both individual and collective investment in acquiring knowledge for future application (Busby 1999).

Petroski warns that there is clearly no guarantee of success in designing new things on the basis of past successes alone, and this is why artificial intelligence, expert systems, and other computer-based design aids whose logic follows examples of success can only have limited application. It is imperative in the design process to have a full and complete understanding of how failure is being obviated in order to achieve success. Without fully appreciating how close to failing a new design is, its own designer may not fully understand how and why a design works (Petroski 1994) p 31. In the civil aerospace studies an example of an obsolete process had been included in the design (CAS C4).

6.4.10 Lack of feedback - no learning from queries and concessions on current work

Factor 10g is that systems for dealing with design queries and concessions are often bureaucratic and cumbersome, and may be dealt with by a separate department. This can have a number of consequences:

- People on the shopfloor may be reluctant to raise queries, knowing that responses are slow and work in progress must be quarantined until answers are received;
- The post-Design service department may address the symptom rather than the cause, treating each query or change request in isolation. They may fail to grasp the opportunity to look for similar errors or omissions in manufacturing information for other parts in current production. In the worst-case, their solution may compromise the original design intent;
- Because the subjects were not raised, or were dealt with by others, the original design team may not become aware of difficulties in production, and hence perpetuate them in future designs, as for Section 6.4.9 above.

This factor was found during the civil aerospace study (CAS A3).

Busby expresses concern that the error-correcting function of feedback was compromised by the poor diagnostic abilities of people in other functions, and by the superficial level of peer reviews. Delays in detecting errors also meant that designers were disinclined and had too few resources to correct them thoroughly. In terms of the learning function of feedback, post project reviews were mostly absent and delayed outcomes (like product cost) made it hard for designers to associate important design criteria with specific design decisions or practices (Busby 1997) p107. However, Busby also made the point that there are several ways in which feedback can positively interfere with good cognitive performance. The first is that simple knowledge of outcomes distracts people from applying correct decision models in uncertain situations – for example when estimating the properties of materials or performance of structures. It seems that knowledge of *specific* outcomes is a distraction to which people attribute too much predictive content. Secondly, outcome feedback can lead to over-confidence in the decision strategies – not so much leading to wrong predictions but to unwarranted belief in one's predictions... such as the bias towards attending to information that confirms rather than contradicts initial beliefs (Busby 1998) p105.

6.4.11 Wrong standards, when correct standards available

Factor 11c is where training and experience are needed to prevent out-of-date or inappropriate standards being called up (AXP).

Factor 11d is where specifications unnecessarily limit the permitted standards appropriate to the processes that may be used. Boston et al emphasise the importance of the efficient and effective management of design information, including standard supplier information. If this is not current or accurate, then innovation may be constrained or mistakes or misjudgements may be made on aspects of the products' design. This could result in products that are suboptimal or are built around discontinued technologies, or even lead to catastrophic failure. If information is poorly structured, then it may be overlooked, or engineering designers may be unable to locate it in the available time. In either instance, design decisions may be based on incomplete data and assumptions, and they are therefore likely to be suboptimal (Boston, Culley et al. 1999).

Factor 11g is where Manufacturing or Quality fail to query standards that appear out of date or inappropriate, as part of their normal communication and teamworking. During both the AEROEXTN project and the civil aerospace studies it was noted that Manufacturing and Quality accepted that they had been working for many years with tolerance standards that were no longer the most appropriate for the type of work they were doing (AXP and CAS).

6.4.12 Information not shared by Design for commercial, political, or parochial reasons

Factor 12g occurs when Design will not share information. Willingness to share information may be more important than the mechanism for doing so. Ashkenas et al categorise barriers to communication as follows (Ashkenas, Ulrich et al. 1995) p 204:

- **Legal and regulatory tradition** – collaboration is often viewed as collusion or restraint of free trade. Not all arrangements will be viewed as having pure motives, and some may require costly lobbying or time-consuming justifications to dissuade regulatory bodies from seeing restraint of trade.
- **Competitive confusion** – the potential to force companies to place their bets with one value chain as opposed to another or, at least, to cause confusion about who is an ally and who is not. Identifying these potentially contradictory relationships and weighing the trade-offs is a major but essential task for companies that want to establish boundaryless relationships with customers and suppliers.
- **The trust barrier** – the chasms caused by the lack of trust across companies can be much deeper than those from the internal conflict between functions or departments, yet a great deal of cross-company interdependence is required if the overall value chain is to succeed. That interdependence is based on trust,

which must be nurtured and encouraged, so that lack of it does not poison relationships and weaken the entire value chain.

- **The control barrier** – executives must become comfortable with control sharing: collaborative, collegial, consultative arrangements with a range of business partners. When the external boundaries are loosened, no one member of the value chain will be able to dictate arbitrary terms and conditions to others. With limited numbers of strategic partners, companies cannot afford to force a one-sided agenda that might weaken the chain by causing a partner to walk out or collapse. Participants should focus on creating a collaboration with suppliers and customers that would control the entire process from beginning to end, rather than each seeking to control just its own 'internal' piece of the value chain process.
- **The skill barrier** – the need to develop a new set of managerial skills to replace the traditional use of authority, reward and punishment, and control of resources. Specifically, managers must spend more of their time on the interface between links in the value chain, managing relationships there rather than negotiating terms and conditions. In this role, managers need superb listening skills, a variety of problem-solving techniques, and an ability to build consensus.
- **The complexity barrier** – no matter how straightforward the business interests and the content of a collaboration, there are always a multitude of variables that can influence success, and many of them cannot be fully controlled or predicted in advance. They include shifts in the business climate, changes in government regulations, and developments or frustrations in technology. Collaboration also requires an ongoing match between the business goals and needs of the partners. It is not enough merely to establish a customer-supplier partnership; that is only the beginning. Once initiated, the partnership must be continually re-calibrated, adjusted, tested, assessed, and reworked. Otherwise, the complexity may become overwhelming.

In the case of the civil aerospace study of external supply, there had been a degree of uncertainty regarding the strategic sourcing of parts. This had made Design reluctant to incorporate site-specific changes for the benefit of a particular supplier while there was a possibility that the work may be done elsewhere, perhaps at a later stage in production as part of an offset arrangement or as a result of multiple sourcing to increase production capacity. This could have had an influence on the composite parts where Design considered the requests for change to be site-specific (CAS C2,3,5,6,9,and10).

6.4.13 Information not shared by Manufacturing for commercial, political, or parochial reasons

Factor 13g embraces the same considerations as 12g above, and is especially significant when manufacturing is outsourced. Suppliers may not wish their customers to reveal their processes to rival suppliers. The CEO of a microchip design firm discussed the difficulty of how the intellectual property from multiple vendors could be brought in and merged into one design, and claimed that this problem was slowly being solved (Takahashi 2000).

6.4.14 Failure to consult/involve suppliers, including third parties (e.g. material suppliers, sub-contractors)

Factor 14c is the need to train people to make full use of their suppliers' expertise. The organisation may not train designers to be aware of the details of the supply chain, or its significance in the manufacture of their particular design. Suppliers can be a rich source of information and ideas, and they in turn can benefit from their suppliers.

In the AEROEXTN project, Design showed the team a CAD model of the SESAME assembly, illustrating how the associated parts fitted. After seeing this, the production engineer proposed a design change that would have made a significant improvement for Manufacturing. In this instance, Design agreed that the proposal had considerable merit, but the change could not be accepted for other technical reasons. However, this issue did illustrate the potential benefit of fully involving the supplier and inviting radical suggestions (AXP S13).

In the civil aerospace study, the supplier of hard metal parts was able to provide the benefit of their expertise in preventing the risk of damage to the main part, by proposing the insertion of a bush to retain a grease nipple (AXP T4). In the case of composite finishing, the supplier was able to advise on the use of Synskin to reduce the overall cost of finishing the panel surface (CAS C13).

Contact with third party suppliers is likely to become more remote as current trends towards reducing the number of first-tier suppliers continues. The consultancy AT Kearney recently reported that the big aerospace companies were planning to cut by 80% the number of suppliers they used and were bringing in experts from the car industry to help them achieve this. The report, supported by the Society of British Aerospace Companies (SBAC), warned that component suppliers would have to be fewer in number and further removed from the main manufacturer, and may have to accept a lower position in the supply chain, rather than a direct relationship with the prime contractor (Renton 2000). Training courses may therefore need to emphasise the importance of learning to follow changes in the supply chain as far down as may be necessary to ensure that the processes involved in manufacture are fully understood and taken into account during design.

A manufacturer of robots for the automobile industry was enthusiastic: "We may be smart in applying robots, but we don't know a lot about product design. However, we might give you some ideas you have not thought of yourself. Similarly, when you talk to us about your designs coming forward, we can look at what we would really be able to do. We're doing some of that with material suppliers. They're using different kinds of materials, and proposing them for different parts of the automobile and for other products. That gives us a chance to develop a robot that can apply a new coating in a new way, for example, or that can do welding in different ways." (Chief Executive 1999).

Recognising the increasing importance of environmental regulations, Plaut points out how an 'environmental manager' may help the design department by warning of products or processes, such as those using cadmium or arsenic, which may cause problems for the company or its customers. It would be part of his job to spend time educating the designers, helping them understand that there are alternative materials and that they may have to work hard to find them. The end result may often be higher efficiency, safer manufacture, easier regulatory clearance, greater customer receptivity, and avoidance of costs and liability (Plaut 2000) p 470.

Factor 14g is the difficulty in organising the communication and teamworking to ensure proper involvement of Design with Manufacturing and Purchasing so that the significance and impact of decisions on the supply chain are appreciated. Such involvement should be matched to the context. Bensaou proposed that the product exchanged, its technology and the capabilities of the suppliers available should be included as key environmental factors to define the contextual profile of the relationships to be managed. Some relationships may benefit from investing in building trust through frequent visits, guest engineers, and cross-company teams, while for others the product and market context might call for simple, impersonal control and data-exchange mechanisms (Bensaou 1999).

6.4.15 Failure to anticipate problems

Factor 15c is the failure of Managers and supervisors to ensure that all concerned have appropriate training or experience to anticipate problems in the relevant area.

Factor 15d is company procedures that do not have checklists or review meetings that are effective in prompting people to anticipate problems.

Factor 15f is the inability of tools to anticipate problems outside the historical database from which they have been derived, or to take into account local conditions unless they have been specially developed for this purpose.

Factor 15g is where teams do not actively look for and discuss possible problems. In this respect, the proportion of unanticipated problems may be set as a team metric (see Section 6.4.8).

The aerospace industry appeared from the best practice study to have a different approach from the automobile industry to maintaining the development schedule: a launch date for a new car may be regarded as sacrosanct, especially if it is planned to be unveiled at a particular motor show. The idea of 'baring your chest' - volunteering problems and highlighting early slippage for communal recovery effort - can encourage team members to anticipate problems and plan alternative approaches before the programme is jeopardised. However, the barriers listed in Section 6.4.12g may have to be overcome to prevent potential slippages from being declared, e.g. for contractual reasons (BPS).

Conley reported that the project advisor to a company developing a new small 4-stroke engine regularly interjected his fundamental operating philosophies: "The biggest problem we have is the one we don't know about" and "If this design fails, do you have a fall back plan to keep us on schedule?" (Conley 1998) p 28.

6.4.16 Lack of ability

Factor 16g is because team members with the highest level of ability cannot be allocated to every project. It is, however, possible to make the most of the available abilities. In his notes on self-actualisation, Maslow explains how identification with important causes, or important jobs, enhances self-esteem and is a way of overcoming actual shortcomings in IQ, in talent, in skill etc. If we believe in the potential of people and that people are most important organisational assets, he asks why do we frequently design organisations to satisfy our need for control and not to maximise the contributions of people? Lack of ability can therefore be seen as an organisational problem related to the development of communications and teamworking, since this should foster self-esteem (Maslow, Stephens et al. 1998) p 11.

6.4.17 Lack of effort

Factor 17g is lack of motivation to encourage effort, even amongst the most able, and is very much influenced by leadership, teamwork and communication. The motivation of the project leader is particularly important. R.J. Might commented on a study in which there was a clear correlation between responsibility and project success: only one project manager who was not given some increase in responsibility was associated with a project whose technical performance was above the median (Might 1984) p 129.

Maslow supports the connection between motivation and responsibility, but warns that there is a balance to be struck. He states that everyone, but especially the more developed persons, prefers responsibility to dependency and passivity most of the time. This lessens if the person is weak, frightened, or sick or depressed etc., therefore responsibility must be set at the right level for them to manage it well. Too much responsibility can crush the person just as too little responsibility can make them flabby. Pace, level etc., must be taken into account (Maslow, Stephens et al. 1998) p 20.

6.4.18 Lack of time

Factor 18g is where sub-optimal processes or procedures have to be adopted because people involved in downstream activities were prevented from raising matters concerning long-lead-time processes, owing to lack of early awareness of the project programme.

Designers and others may claim they do not have time to examine or discuss certain possibilities, but when things go wrong everyone finds the time to sort matters out ('fire-brigading'). Aviation Week and Space Technology reported a case of extensive investigation and rework following production problems at a major civil aerospace manufacturer. These should have been avoided by greater co-operation and teamwork to ensure the correct procedures and processes had been specified and understood (McKenna 1999).

To encourage people to address issues early, L. R. Smith et al suggest allocating engineers by disposition/job – using 'fire-fighters' only at the end of programs, and people with 'prevention' mentality up-front on programs. 'Certified' engineers or former quality office engineers should form more than 20% of the population in any new model program (Smith, Zlotin et al. 1999).

6.5 Technical

Table 6.5 Technical problems related to sources of information and influence

	TYPE of REASON for PROBLEMS	Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking
a	b	c	d	e	f	g
1	Changes in circumstances (manufacturing equipment)					x
2	Constraints of CAD system			x		
3	Failure to convey design intent					x
4	Compatibility of CNC tool path generation			x		x
5	Inappropriate standards -- existing standards do not match requirements		x			
6	Inadequacy of database information				x	x
7	Sub-optimal solution from DFM software				x	
8	Errors in CNC tape generation software				x	
9	Malfunction of machine (e.g. tool breakage)	x				
10	Format/translation problems		x			x
11	Difficulty in representing features on model/drawing			x		x
12	Material not best matched to process and geometry	x	x		x	x

6.5.1 Changes in circumstances (manufacturing equipment)

Factor 1g is the lack of notification of change in process, equipment, or capability since previous work or supplier. The timeline is vitally important here: with so many changes resulting from rationalisation, reorganisation, re-equipment and loss of traditional skills, there may be significant differences between the advice given during the early design stages and that which would be appropriate when the time comes for manufacture. While some changes may be documented and circulated or put on a database available to all concerned, there may be no trigger to initiate design action to allow for them. This may be overcome by communication and teamworking to bring the right people together from amongst Design, Manufacturing, Procurement, Quality, Transportation, Packaging and Finance as necessary to anticipate the consequences and take action accordingly. Examples of problems to be overcome in this area include:

- Phasing out of machinery/process – derivatives based on earlier design concepts can no longer be produced. Anticipating this may allow the production batch to be completed before the facility is dismantled, or allow time for a redesign to take advantage of new processes and a cost-reduction exercise.
- Introduction of new machinery/process – designs may not be optimised to take advantage of the new capability. Conversely, the new process may not live up to its expectations and extra cost may be incurred in redesign or scrap and rework.

- Changes in capacity – manufacture may be outsourced (or brought back in house), the supplier may change (or sub-contract to a third party), so that different facilities are to be used. This may have a variety of implications, including that of data exchange standards, material sourcing, packaging and transportation between sites.
- Change in personnel – those who have to implement what was previously agreed may contradict advice given earlier.

In the civil aerospace in-house study, Manufacturing had requested a number of Engineering Changes to allow the use of 5-axis machining features in place of using angled cutters in 3-axis, or 5-axis scanning. Manufacturing did not use special cutters, owing to the cost and difficulty of maintaining them (CAS A1).

In the best practice study, an aerospace company had produced a full set of 2D drawings from their 3D design model at the request of their chosen supplier, who did not have a 3D capability. When the parts were required, however, the supplier was short of capacity and subcontracted the work to a machine shop that could work directly from the 3D model. Considerable design effort might have been saved by an early decision to sub contract these parts (BPS).

6.5.2 Constraints of CAD system

Factor 2e occurs where the CAD software favours particular build-up sequence, geometry or features that do not favour the production processes. Stacey and Eckert concluded that designers could only create what their tools make possible, and they were pushed strongly towards creating designs that their tools made relatively easy. Some effects stemmed from inherent limits of software, but others were due to inadequate human computer interface (HCI) design. For example, design tools may bias designs by influencing the process by which they are created (e.g. if designers were forced to make certain decisions before others). Tools that were poor, or were used in unanticipated ways, could push designers into premature commitments to decisions, that were based on inadequate information or were purely arbitrary – these were likely to be biased towards what is simple, obvious, standard, or what the designer liked. This could force the acceptance of suboptimal designs. CAD system development involves making a trade-off between minimising unevenness and bias and maximising simplicity and ease of use. Adding features and parameters to a tool has two kinds of costs: complex tools are harder to learn, and each action is harder or slower to make because it has to be selected from a wider range of alternatives (Stacey and Eckert 1999) p1414.

In the AEROEXTN project, the SESAME designer had modelled four symmetrically-arranged features on the circumference of a cylindrical part using the CAD 'rotate' facility, on the assumption that these features would be made by rotating the work piece before each cut. The supplier, however, was happy to accept such features generated by mirroring, which would have been much easier to model on that CAD system (AXP S4).

6.5.3 Failure to convey design intent

Factor 3g is where missing or inadequate information results in Manufacturing failing to meet design requirements or wasting resources (e.g. working to unnecessary tolerances). Pahl and Beitz provide a checklist for evaluating embodiment designs at an early stage for potential problems. The production aspects include looking at risk-free methods, setting-up time, heat treatment, surface treatment and tolerances (Pahl and Beitz 1995) p 311. Production engineers can be encouraged to offer recommendations for improvement by designers explaining the design intent during teamworking, where otherwise they would not have queried the manufacturing information with which they were tasked (AXP S2).

The problem of interpretation (so-called 'grey areas') was discussed at length during the AEROEXTN Project, where Quality offered an example of a part that had failed sample approval because of distortion. They had found that some 30 to 35% of mechanical part rejections were for plating, painting, and finishing – e.g. obscure paint processes; interpretation of 'gloss' or 'substantially free of defects' (is a mark a defect?); thickness of paint; part marking (if the correct ink and varnish was used, but the writing was illegible, was the part correctly marked?). The requirement for a particular missile to be painted inside and out had involved more time to mask up the complex parts than it had taken to machine them. In the case of the SESAME parts, the production engineers queried the design intent for the alignment of the bores of pairs of piston holes: they wanted to know whether it was important for the axes to coincide, because this would determine their choice machining set up (AXP S7). Further information was also sought on the engraving of nozzle numbers and of part marking for SESAME (AXP S10, S11).

A solution adopted by civil aerospace to the problem of defining surface finish standards in a readily-understood manner was for the customer to provide Manufacturing with go/no-go sample panels, showing an acceptable finish on one side and an unacceptable finish on the other (CAS).

6.5.4 Compatibility of CNC tool path generation

Factor 4c is the adverse affect that the sequence of generating CAD model geometry may have on the ease of CNC programming.

The CAD model for the part can make a big difference to the ease with which the subsequent NC programme can be generated to create the tool path. It may also be difficult to match the CAD surface geometry without using special tools; e.g. a smooth concave surface with a double curvature might need a barrel/ball cutter for accurate reproduction, whereas a design permitting a ruled surface could be produced more quickly and cheaply with a rectangular cutter. McMahon explains the use of 3-axis and 5-axis machines to produce a double curvature form, including the trade-off between cusp size and the number of machining paths used. Even with a very small step-over between adjacent paths, and hence small cusps, some hand-finishing may still be required (McMahon and Browne 1993) p 324.

Factor 4g is where a lack of liaison to align the design approach to the CNC tool characteristics may result in geometry that is difficult to programme or execute. The civil aerospace studies showed examples of trade-off: designers had to be persuaded to accept a small penalty in shape to allow machining to proceed more quickly and economically (CAS A1-2; T1-3). Such changes may also allow the use 3- or 4-axis instead of 5-axis machines. As well as making use of lower-cost machines, this could be an important factor in broadening the potential supplier base to expand capacity or to participate in offset agreements (CAS).

6.5.5 Inappropriate standards – existing standards do not match requirements

Factor 5d occurs where standards lag behind practice, and may be over-prescriptive, irrelevant or inadequate for the required processes/materials. Both the AEROEXTN project and the civil aerospace studies found that the standards used to specify mechanical tolerances were based on those developed many years ago, when machined parts were not made in such large sizes. For example, absolute tolerances were specified according to size, but the largest size specified was 'over 500 mm, ± 0.5 mm'. While this represented a latitude of 0.2% in a 500 mm dimension, it would be nearer 0.03% for a 3 m part. Such a 3 m aluminium part would alter its length by the whole of this latitude if the temperature changed by only 7 degrees, although the standard did not specify the temperature. New standards of geometric dimensioning and tolerancing should ensure greater clarity of intent (AXP and CAS A5).

6.5.6 Inadequacy of database information

Factor 6f is where the DFM database contains errors, or the constraints on its applicability may not be apparent to users (BPS). Minis et al pointed out that traditional manufacturability evaluation approaches are useful for comparing the relative cost and time when the manufacturing process is known and standardized but may be insufficient and may lead to poor designs when there exist alternative process plans and a choice of subcontractors that have different capabilities (Minis, Herrmann et al. 1999) p 387.

Factor 6g occurs when the DFM tool users fail to communicate such shortcomings to the appropriate support group, so that they are perpetuated. The civil aerospace studies found an example where the supplier was used to working with a particular software package for composite ply placement, but this was not developed to work well with the customer's Design Office CAD. Design had to outsource this aspect to a third party before being able to provide the supplier with the design information required (CAS C6).

6.5.7 Sub-optimal solution from DFM software

Factor 7f is where the application is not optimised for the process/material combination. Petroski points out that efforts to improve engineering design by concentrating on the refinement of its more easily-quantifiable analytical models and tools may actually be counter-productive if those efforts come at the expense of studies aimed at improving the assumptive and interpretive skills of engineers (Petroski 1994) p 184.

6.5.8 Errors in CNC tape generation software

Factor 8f is that the software may not be matched for the process. Petroski asserts that the development of computer aids for design and other aspects of engineering cannot be expected to be free of error, and denying, de-emphasising, or ignoring this fact can only create a climate even more hospitable to error than one in which it is high in the consciousness of those working on engineering design problems or on the development of computer software to attack them. Computer aided design tools created in a methodological vacuum devoid of past experience are likely to provide more than their own fair share of case studies of error and failure for the next generation (Petroski 1994) p 182.

6.5.9 Malfunction of machine (e.g. tool breakage)

Factor 9c is the lack of familiarity with machine set up and operation. Peklenik describes the complexity of the machine tool in manufacturing. The performance depends on: the time-dependent geometrical and physical parameters of the machine tool performing the machining; tooling; the ability of the CNC control system to follow the reference instructions with an accuracy required; the ability of the control system to adapt the machine tool when the disturbances (tool wear, thermal deformation, vibrations, etc.) affect the performance of the machining system.

Peklenik provides examples of complex manufacturing processes such as grinding that include random effects. A secondary source of disturbances is wear, adding to the stochastic. However, such secondary effects can suddenly trigger major perturbations that may lead to catastrophic events such as tool breakage, etc. (Peklenik 1999) p34.

In the civil aerospace in-house study, Manufacturing were gaining experience with their new 5-axis machining centre, and were learning to cope with practical limitations that included the thermal effects of high-speed machining. They recognised that even with hot probing of the dimensions they would be unlikely to meet the very close tolerances originally requested by Design without adding a fourth stage to the machining process or selecting pallets (CAS A4).

6.5.10 Format/translation problems

Factor 10d is the lack of use of standard formats to promote accuracy, consistency and interoperability. Court found that a significant issue for the integration of knowledge in new product development was the need for agreement on an appropriate format for information and knowledge presentation that will be shared between users. Currently information is presented in a multitude of formats and languages, which significantly affect its future applicability and usefulness; the same can be said of knowledge. However, the format of the information within the sources is beyond the direct control of the engineer; but even when it is, major difficulties arise because they frequently transfer information in the format that is easiest for the originator. These problems also extended to electronic data, as the existence of many types of software and various methods for data representation implies that data provided by one source is likely to require some manipulation to the format understood by the end user. It was important that formats should cater for the nature of the information and knowledge used by engineers (Court 1998) p 394.

Schmitz reported that audits of data models showed a very high proportion that did not fully meet quality standards. Not only does this add rework time and cost downstream locally, but it also reduces the capacity for data to be exchanged between different software systems. The results of these quality audits were consistent with research conducted by the US National Institute of Standards and Technology (NIST). A March 1999 study by NIST showed that interoperability problems due to data quality errors within the automotive supply chain alone could cost as much as $1 billion a year. One reason digital models fall short of standards is the inherent flexibility of product modeling software systems that offer engineers a number of ways to create, assemble, and annotate a digital model. Without defined guidelines, the danger is that each designer will create models according to his or her own individual methodology, rather than in accordance with company standards. As the audits discovered, this causes problems because even designers on the same team may not be able to make simple changes to one another's designs (Schmitz 2000).

Quality problems with digital data may be considerably reduced by the use of software such as DesignQA, which compares solid models generated by designers and engineers to their company standards and good modelling practices and reports discrepancies. This software includes a checklist of over 130 design standards based on best CAD practices. After identifying a model that does not follow administrative standards, DesignQA alerts the designer, explains the standard the designer violated, and either fixes the problem or suggests a correction (Rosinski and Brooks 2000).

Factor 10g concerns the missing or incomplete features or annotations in translating or interpreting file formats. Prasad lists many categories of potential data loss occurring during the translation process, including: inaccuracies; incomplete or extraneous information; missing data; ripples; and instabilities (information layers, dimensional intelligence, non graphics information, connectivity information, components configuration information, routing information, or alteration of text or fonts) (Prasad 1997) p 369.

Owen concluded that, despite all the expertise utilised in generating STEP protocols, problems would arise even when data exchange was undertaken using two performance-tested processes of a well-defined standard written using formal methods. He considered product data exchange was unlikely to become 'appliance' or 'black box' technology in the near future, if ever (Owen 1997) p 131.

In the civil aerospace studies, the outsourced supplier received design models on a workstation with the same CAD software as the designer, and then translated it to his own CAD software for production. This translation was not without its difficulties, but in this case the supplier could readily check on the design model without having to contact the customer (CAS).

In the best practice study, one manufacturing supplier also had a design division, which contributed some design work to the customer. Although they had used notionally the same version of the same CAD software as the customer, they had not received the same support as their customer from the CAD supplier to fix some anomalies ('bugs') in the software. In consequence, they had to pay for their model to be harmonised before it could be accepted (BPS).

6.5.11 Difficulty in representing features on model/drawing

Factor 11e is that software varies in ease of presentation. McMahon and Browne observed that even though systems concentrate on the modelling of designs, the range of properties that are represented is limited. Properties that might be modelled include form, dimension, tolerance, material, surface condition, structure and function, but it is only the first two of these are covered extensively in CAD – the others are generally covered by annotations of a drawing, or by attaching attributes to the three-dimensional model. A system that captures a complete model of product will require annotations for all the properties of the design. Furthermore, CAD systems may not model even the geometric aspects of the design in the way that designers think of them. For example, a connecting rod might be represented by a collection of lines and arcs on a drawing, or by surfaces on the part, or by instances of solid primitives. The designer, on the other hand, may envisage the part as two 'eyes' joined by a 'shank', or might think in terms of manufacturing features such as a reamed hole, a blend or a flash-line (McMahon and Browne 1993) p 216.

A production engineer on the AEROEXTN team presented an example of three dimensioning schemes, showing how the supplier's Manufacturing Department, the supplier's Quality Department and the customer's Quality Department could each apply (quite correctly) a different dimensioning scheme to meet what was notionally the same general tolerance requirement. This could result in 'vicious circles' of parts being made, rejected and returned, rechecked and nothing found wrong. One way to ensure a correctly manufactured and inspected product would be to indicate every dimension on the model or drawing in the position intended by the designer, especially if the parts were to be made on a manual, rather than a CNC machine (AXP).

Factor 11g is the problem of understanding among team members caused by lack of clear representation of features. Ehrlenspiel et al reported that this is most frequent in the context of unclear or missing sketches and illustrations. Supplementary information or views may be required (Ehrlenspiel, Giapoulis et al. 1997).

AEROEXTN team members were aware that a common vocabulary could be a barrier to communication when discussing features and capabilities. It was too easy to make assumptions of knowledge and about the meaning of terminology (e.g. 'cleat' or 'shear angle'; 'point' or 'vertex'; did 'long-bed machining' refer to 3m or 30m beds?) (AXP).

6.5.12 Material not best matched to process and geometry

Factor 12c occurs because Manufacturing may not be familiar with working the proposed materials with existing equipment, or designers may not be familiar with the geometric features that help and hinder production by various processes. Training for production engineers and for designers should ensure that they are familiar with the principles involved, such as those set out in textbooks (Pahl and Beitz 1995), (Matousek 1963), (Bralla 1986) and (Boothroyd, Dewhurst et al. 1994).

A number of the easements requested in both the AEROEXTN project and the civil aerospace studies were for textbook examples of geometry that was awkward to machine. For example: a rectangular slot with radiused corners was changed to have semicircular ends, so that a single cutter could be used; spot faces would allow the drill to enter normal to the surface, instead of at an angle; a larger-radius cutter would machine deep pockets quicker (AXP S1,5,6,9 and CAS T2).

Factor 12d is where standards and reports do not fully cover process limitations, and should be revised and expanded to avoid future problems. Suppliers' catalogues and brochures are likely to specify their capabilities under ideal conditions, emphasising what they can do well. Further investigation may be needed to identify side effects and characteristic sub-issues (Chen 1998) p 122. In the civil aerospace in-house study, the specification for the machining centre defined accuracy sufficient to meet the tolerances called for by Design. Such accuracy was possible, but only if the work piece had been mounted on a specified pallet or a fourth machining stage had been added to allow the work piece to cool down before the final cut (CAS A4).

Factor 12f occurs when the proposed materials and processes are not on the database for the DFM tools used, or the tools are not capable of automatically interpreting every geometric feature. Gayretli and Abdalla developed a prototype knowledge-based tool for machining process optimisation. This used a combination of both mathematical methods and constraint programming techniques to provide designers with the evaluation and optimisation of feasible machining processes in a consistent manner at the early stages of the design process. However, the best use of available alternative processes and concurrent consideration of manufacturability analysis and process evaluation and optimisation had not yet been fully exploited (Gayretli and Abdalla 1999) p 655.

Where DFM tools are highly developed, and the designer relies heavily on them for taking care of Producibility matters, the point made in Section 6.1.6 by Reason in connection with operator training also applies: "the most successful automated systems with a rare need for manual intervention may need the greatest investment in operator training" (Reason 1997) p 42.

Factor 12g is when Design does not receive feedback on material behaviour under processing, or on previous problems or alternative processes. Discussion may lead to changes to allow use of stock size materials to eliminate or modify processes.

Todd gives, as examples of redesign for ease of manufacture relating to materials: altering the dimensions of a nylon spacer to suit available raw materials so that a machining operation could be eliminated; and (at the suggestion of a production specialist) redesign of a brass fabrication as a pressing which could be manufactured in-house, saving DM63,000 per year for a one-off tooling cost of DM24,000 as well as reducing lead time and stock holding. Also, purchasing cost reductions were achieved with the help of design staff replacing specific requirements with a generic description, or including alternative manufacturers' products, so that buyers could identify alternative sources. Increasingly designers and production specialists were working more closely with their opposite numbers at the suppliers in order to find ways of improving product performance and reducing cost (Todd 1995) Page 259.

Ashby emphasises that the final choice of materials will often depend on local conditions, such as the existing in-house expertise or equipment, on the availability of local suppliers, and so forth. A systematic procedure cannot help here – the decision must instead be based on local knowledge (Ashby 1999) p 68. An example of the use of local knowledge in the AEROEXTN project was the offer of alternative steel to a higher specification, which would have been cheaper than the specified material for the small quantity required, because the supplier used a lot of it for other work. Although notionally cheaper, the original material had a minimum order quantity of several times that needed, together with a 3-month delivery forecast (AXP).

In many cases there will be a conflict between the Producibility requirements and the performance requirements that can be resolved only by negotiation, referred to in Section 6.2.3g . A number of examples were found in the civil aerospace studies, where

Design were persuaded to accept a weight penalty, additional design effort or increased material costs to simplify and speed up the manufacturing processes (CAS A4,5; T1-4; C1,2,5,6,7,9,10).

6.6 Summary

Table 6.6 Types of problem related to sources of information

TYPE of PROBLEMS	SOURCES of INFORMATION and INFLUENCE					TOTALS
	Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking	
Human error	6	2	3	0	5	16
Culture/social	1	1	1	1	10	14
Knowledge	4	3	1	3	4	15
Organisation	5	2	0	3	17	27
Technical	2	3	3	4	7	19
Totals	18	11	8	11	43	91
Total%	20%	12%	9%	12%	47%	100%

A total of 91 factors were identified as potential sources of problems. For the purpose of this analysis, these factors were divided into human (72) and technical (19). Human aspects were further divided into four categories: human error (16); culture/social (14); knowledge (15) and organisation (27). These are summarised in Table 6.6.

6.7 Conclusion

It was found that communication and teamworking (47%) was by far the most important source of information and influence for designers, relating to twice as many factors as training and experience (20%). Standards, specifications, reports and textbooks (12%) matched DFM databases and tools (12%), ahead of CAD systems at (9%).

The results show the prime importance of communications and teamworking in resolving potential manufacturing problems, so as to prevent their reaching the shopfloor. They can be used alongside the Producibility Interaction model for structuring the Concurrent Engineering process to achieve design for manufacturing.

Any organisation could use this analysis to review the nature of their reported DFM problems, conduct root cause diagnosis and allocate resources in a wider business sense to areas capable of contributing the greatest benefit to the DFM process.

Chapter 7 Validation Illustrations

This chapter shows how the issues from the AEROEXTN and civil aerospace case studies could be mapped to the relationship tables, covering step 14 of the methodology set out in Chapter 2.

The industrial validity of the relationship framework is then discussed according to the criteria to be met in order to ensure the practical relevance of this research, as identified in Chapter 2.

7.1 Applying the industrial cases to the framework

The 38 issues raised during both the AEROEXTN project and the civil aerospace studies from Tables 3.2 and C1-3 were set out and examined to see what they had shown in the way of relationships between their nature, where they might have been picked up if there had been no producibility interaction, where the information to prevent them might have lain, how they cross-referred to the subjects in the PI Table. These relationships are shown in Table 7.1. Most of the headings are self-explanatory, and cover material extracted from data captured as described in Chapter 3, Appendix B and Appendix D. The serial numbers in the first column relate to the issue numbers in Tables B1 (S=Sesame stainless steel), D.1 (A=aluminium) and D.2 (T=titanium; C=composite). The following paragraphs explain how the entries were derived for negotiated trade-offs and Chapter 6 factors.

7.1.1 Negotiated trade-offs

None of the SESAME issues had involved any conflict between the Producibility requirements and the performance requirements that could be resolved only by negotiation, as suggested in Section 6.5.12g, and might have made Design reluctant to adopt the suggestions or recommendations of the supplier's production engineers. However, a number of issues in the civil aerospace studies had involved negotiation with Design (usually with Purchasing and Quality in attendance) before requests from Manufacturing were accepted. The particular significance of these issues is that Design may well have been aware that a feature was awkward to manufacture, but did not alter the original design because of the perceived cost or performance penalties. A column has therefore been included to draw attention to the issues that required a negotiation or trade-off (Neg tr/ off?).

7.1.2 Mapping the issues

Each issue was analysed to see how it might best be mapped to the factors in Chapter 6. The following questions were considered for the each of the five categories of reasons in turn:

- Could the issue have arisen because of any of the types of reasons in that category?
- If so, which types of reasons?
- For each type of reason, which factors were relevant?

Once the factor or factors in that category had been identified as relevant, the next category was considered. Any number of factors could be accepted as helping to show why each issue had arisen.

It was important to check that the framework completely covered all 38 issues. After confirming every issue was related to at least one factor, further questions were addressed for each issue:

- Did the factors identified so far completely cover all aspects of the issue?
- If not, should a new factor or factors be introduced to the framework?
- If so, did this show one or more new types of reason?
- If so, did these fit properly into the existing categories?
- If not, what new category or categories were required to expand the framework?

No new factors were identified from the latter set of questions. This was expected, since issues captured during the industrial studies had been included in the process for generation of ideas for developing the framework. However, the framework was expanded to include illustrations from the specific industrial issues.

Table 7.1 Issues raised during producibility interactions

Ser	**Issue**	**Type/ nature**	**Where picked up**	**Where info available**	**Neg tr/ off?**	**PI Table subj's**	**Chap 6 Factors**
S1	Mismatch undercut and rear face	Machining marks	First article	Textbook	No	22, 27	6.3.2c 6.5.12c 6.5.12g
S2	Operating lengths - fit diameters requested	Tolerances—extent	Never, unless tolerances not achievable	Textbook	No	10	6.5.3g 6.5.12c
S3	Tooling hole needed	Tooling	Manu Planning	Manufacturing	No	23	6.4.7f
S4	Supplier happy to accept CAD modelling method producing mirrored features, whereas Design had assumed generating them by rotation would help manufacturing	CAD modelling method	Never	Supplier process knowledge needed		24	6.5.2e
S5	Change rectangular slot with small radius to full radius end	Reduce number of cutting tools and machining operations	Manu planning	Textbook	No	24	6.3.2c 6.5.12c

Ser	Issue	Type/ nature	Where picked up	Where info available	Neg tr/ off?	PI Table subj's	Chap 6 Factors
S6	Request for slot width to be increased due to concern about cutter head distance to wall; feature could not be changed, but wall height could be made smaller to facilitate cutter	Tool clearance	Tape proving	Textbook, but Manufacturing experience needed	No	24	6.5.12c
S7	Alignment required for piston hole	Design intent for datums	Manu query on sight of initial model	Designer: to be shown on drawing	No	11	6.5.3g
S8	Tooling hole size and position discussed	Tooling	Continuation of Issue 3	Manufacturing	No	11	6.4.7f
S9	Add 8 off spot faces to M4 holes	Ease of machining	Manuf planning	Textbook	No	23, 24	6.3.2c 6.5.12c
S10	Engraving - can it be done by hand?	Supplementary process	Manu Planning	Designer	No	16	6.5.3g
S11	What method of part marking? Omitted from original. Position important	Part marking	QA check of drawings	Checklist item	No	17, 19	6.5.3g
S12	Request to remove tight position tolerance on tooling hole (see producibility issues 3 and 8)	Tooling	Continuation of Issues 3 & 8	Manufacturing	No	10, 26	6.4.7f
S13	Considered replacing 8 small slots with a proposed new slot design	Helpful but unacceptable suggestion	Not technically allowed	Supplier suggestion following sight of assembly model	N/A	24	6.4.14c
A1	Use of 5-axis feature in place of angled cutters in 3-axis or 5-axis scanning	5-axis	NC programming	Drawing changes to allow use of 5-axis features	No	10, 12,13, 22, 24, 27	6.5.1g 6.5.4g
A2	Geometry definition did not allow simple 5-axis machining	5-axis	Production Planning	3-D modelling required	No	(24)	6.2.3g 6.5.4g
A3	Problems and errors with drawings, e.g. dimensions missing, notes and pictorial view not matching	2D drawing errors	Production Planning	Checklist items	No	5	6.1.2d 6.1.3c 6.1.3e 6.2.5g 6.3.2g 6.4.10g

Ser	Issue	Type/ nature	Where picked up	Where info available	Neg tr/ off?	PI Table subj's	Chap 6 Factors
A4	Web tolerancing expected to be too tight with current process	Tolerance beyond capability	Production Planning	Design not matched to process capability	Yes	9, 10	6.2.3g 6.5.9c 6.5.12d 6.5.12g
A5	Tooling hole tolerance too tight	Tolerance beyond capability	Production Planning	Tolerance standard out of date	Yes	9, 10	6.2.3g 6.4.11g 6.5.5d 6.5.12g
T1	Ruled surface added (Pylon)	5-axis	NC prog	Textbook, but weight penalty	Yes	12, 24	6.2.3g 6.5.4g 6.5.12g
T2	Change of corner radius on deep pockets (Pintle)	Allowed faster cutting	NC prog	Required up-to-date manufacturing information	Yes	12, 24	6.2.3g 6.5.4g 6.5.12c 6.5.12g
T3	5-axis landings requested /added (Pintle)	Allowed faster cutting	NC prog	Textbook, but weight penalty	Yes	12, 24	6.2.3g 6.5.4g 6.5.12g
T4	Bush insert for grease nipple hole (Pintle)	Use of supplier's expertise to improve part	Possibilty of damage to hole	Risk reduction	Yes	5, 13	6.2.3g 6.4.14c 6.5.12g
T5	2D drawing GD & T datum errors (Jack)	Datum Designer's error	Inspection	Change of designer – error not picked up before drawing release	No	11, 19, 29	6.1.3c 6.1.3e
T6	Models created to nominal dimn on ++ tolerances (Jack)	Tolerancing error	Inspection	Probable mistake in looking up associated part information	No	11, 19, 29	6.1.2d 6.1.3e
T7	Pintle locking block radius in wrong position	Designer's error 3D CAD model	Assembly	Late part requirement, not subjected to clash detection	No	29	6.1.3c 6.1.3e
C1	Alternate plies of woven and unidirectional carbon changed to all woven ABRI 0023	Material standardisation	Production planning.	Easy to spot, but compromised design	Yes	8	6.2.3g 6.5.12g
C2	Landing areas redesigned to be the same thickness throughout the panel	Legacy – complex tooling	Tooling	Design effort needed	Yes	23	6.2.3g 6.3.2d 6.5.12g
C3	Honeycomb ribbon direction different from earlier panels.	Legacy – caused problem	Honeycomb manufacture	Manufacturing experience of double curvature panels needed	No	8	6.3.2d 6.3.3f

Ser	Issue	Type/ nature	Where picked up	Where info available	Neg tr/ off?	PI Table subj's	Chap 6 Factors
C4	Deletion of outer surface Tedlar film.	Legacy – not needed	Production planning	Lack of design handbook, or feedback from earlier designs	No	8	6.2.3c 6.4.9g
C5	Use of technology from another supplier project for tooling for bonding and routing.	Tooling commonality	Design	Supplier requirement	Yes	23	6.2.3g 6.3.2d 6.5.12g
C6	Use of Fiber-sim for ply development.	CAD/CAM software commonality	Design	Supplier requirement	Yes	17	6.2.3g 6.3.2d 6.5.6g 6.5.12g
C7	One shot foiling of panels.	Production flexibility	Production planning.	Original design too prescriptive	Yes	8, 16	6.2.3g 6.5.12g
C8	Addition of tooling holes for customer assembly jig pick-up.	Customer tooling requirement	Assembly build	Late part specification change	No	8, 11	6.2.4g
C9	All plys to be one-piece plys (ref item 6)	Manufacturing easement	Production planning	Supplier request	Yes	24	6.2.3g 6.3.2d 6.5.12g
C10	Ply drop-offs designed incorrectly for aesthetics.	Inspection requirement	Production planning	Supplier requirement	Yes	16, 17, 26	6.2.3g 6.3.2d 6.5.12g
C11	Incorrect specifications for formed honeycomb core.	Designer's error	Honeycomb manufacture	Wrong material specification (look-up error)	No	8	6.1.2d
C12	Elimination of core filling.	Followed issue C2	Production planning		Yes	23	6.2.3g 6.5.12g
C13	Addition of Synskin for surface finish.	Change to reduce overall surface finish costs	Paint preparation	Consideration of subsequent finishing processes	No	8	6.3.2c 6.4.14c

7.2 Analysis

Each of the 38 study issues raised was related to at least one factor in the Chapter 6 framework, with an average of more than two factors for each issue. An analysis of these factors is summarised in Table 7.2, using the same format as Table 6.6.

The distribution in Table 7.2 shows a predominance of technical reasons, of which more than two-thirds are concerned with communications and teamworking. This may be expected from the way in which the study information was gathered, since each issue was the result of producibility interaction that involved face-to-face communication, and the technical nature reflects the physical aspect of the mismatch between the design and the manufacturing process/material called for. It should be noted that very few issues came under the categories of CAD Systems or DFM databases, probably because designers were reluctant to blame their tools or did not use them.

Table 7.2 Distribution of factors relating to issues

TYPES of PROBLEMS	SOURCES of INFORMATION and INFLUENCE					TOTALS
	Training and Experience	Standards Specifications Reports Textbooks	CAD Systems	DFM Databases and Tools	Communication and Teamworking	
Human error	3	3	4			10
Culture/social					17	17
Knowledge	5	6		1	1	13
Organisation	3			3	3	9
Technical	6	2	1		26	36
Totals	18	11	5	4	47	85
Total%	21.2%	12.9%	5.9%	4.7%	55.3%	100%

7.3 Industrial validity of relationship framework

The five criteria that should be met in order to ensure the practical relevance of this research were set out in Chapter 2 Section 2.7 as: descriptive relevance; goal relevance; timeliness; operational validity and non-obviousness. This section addresses these criteria and their associated questions, and expands on the summary given in Table 2.3 of what was demonstrated by this research.

7.3.1 Descriptive relevance

Does the research capture a 'real' problem for the 'practitioner'?

The industrial collaborators drove the original research proposal for the AEROEXTN Project to investigate concurrent engineering in the extended enterprise. They had already experienced the benefits of in-house CE, and were keen to extend these to the manufacture of outsourced components after they had ceased to make the parts themselves. It was the practitioners from both customer and supplier in industry that gave the subject of producibility their highest priority. The CE template that was developed to set up the SESAME pilot project had the Producibility Interactions as its central activity.

The producibility issues captured during SESAME and subsequent civil aerospace studies addressed very real problems for the practitioners. It was the realisation that these problems could occur, despite the availability of CE and the associated tools intended to avoid them, that led directly to this research question. When mapped to the framework, Table 7.1 shows the type and nature of those issues falling into the 35 types of reasons. This provides confidence that these types of reasons are relevant to the industrial problems, and also shows where the information available falls into the five categories of sources. The factors explain the relationship, and relating issues to the factors shows the power of the framework to provide explanations that can help practitioners to understand the issues.

The author participated in discussions with practitioners at industrial seminars and presented papers at conferences on aspects of the research covered by this thesis. These forums confirmed that practitioners in the whole of the design to manufacture chain recognise the real nature of the problems.

7.3.2 Goal relevance

Is the output of the research related to the objective/function of organisations?

The literature shows that the industrial design to manufacture chain has a competitive imperative to improve their processes. Management techniques such as CE are directed at improving efficiency, reducing time to market and cost. Much effort is directed at improving communication, teamwork, encouraging innovation and inspiring participants. However, the literature also shows that the availability of such techniques does not guarantee their implementation.

The output of this research is intended to help industrial users to identify the factors that prevent their producibility processes from being fully effective. This is directly related to the goal of organisations wanting to improve their efficiency.

7.3.3 Timeliness

Do the phenomena change faster than science can come to grips with the problem?

The phenomena investigated in this research covered the five categories of types of reasons for producibility problems. Of these, the technical & knowledge categories might be affected most by rapid changes in technology. However, while specific technical matters and the associated knowledge may change with advances in technology, the principles of the factors involving the need for effective training, communication and teamworking and the maintenance of standards are unchanged.

The evidence from this research shows that most of the problems are related to the human, cultural and organisational aspects that require good leadership and management to prevent them. Many of the factors involved are not new, but problems continue to arise because of them. If and when the relevant factors alter, the flexibility of the framework would allow it to be amended, expanded or adapted as quickly as the phenomena might change.

The content and structure of the framework enable the analysis of current industrial problems. The acceptance of a paper presented at the 6th ASME DETC/Design for Manufacturing Conference 2001 supports its relevance and importance to the research community.

7.3.4 Operational validity

Can the results of the research be implemented by manipulating causal variables?

The relationship framework was developed as a diagnostic tool so as to draw attention to the causal variables affecting producibility problems in the design to manufacture chain. This was done to draw attention to the reasons why these problems occur. This was intended to help practitioners and researchers address them, and hence work to manipulate the variables so as to eliminate them.

The descriptive relevance (Section 7.3.1 above) gives a high degree of confidence that the industrial issues can all be explained by applying the framework. However, the framework has not yet been tested in industry to prove its utility in practice.

7.3.5 Non-obviousness

Does the research simply reinvent the wheel?

While much of the material presented in this research may have appeared obvious to one or more of the parties involved in the design to manufacture chain, the fact that they were raised suggests that they were not obvious to all. Alternatively, matters were influenced by factors that prevented them from being resolved before they came to notice. In either case, the manner in which the data from industry has been captured and the material from the literature has been selected has been used by the author to derive the categories and to construct the framework so as to present the factors in a way that they provide a fresh insight into the relationships between the types of problem and influences on them.

The relationship framework combines industrial case study experience with extensive illustrations from a wide range of literature. The structure of the framework is not obvious. Published work uses case studies to warn of pitfalls and sets out prescriptive processes to avoid them, but does not attempt to structure a large amount of data from case studies.

The unique opportunity to maintain extensive industrial contact over a long period of time enabled the insight to define the categories of reasons and sources of information in a way that could lead to practical actions by industry managers.

The framework is a practical contribution to industrial practitioners who need to address producibility issues.

Chapter 8 Discussion

Now that the relational framework and its validity have been presented, this chapter discusses the significance of the work in the light of the state-of-the-art published material and industrial practice, and explains how the framework could be applied in an industrial situation to improve the design for manufacture process.

Sections 8.1 to 8.7 discuss the significance of the work, following the structure of the literature review in Chapter 4 to highlight the additional contribution to knowledge of the work under the same main headings.

Section 8.8 explains some possible industrial applications of the framework.

8.1 Concurrent engineering

Textbooks on CE present clear prescriptive directions for the design-to-manufacture process, with the underlying theme that the processes are presented in an idealised form, albeit with warnings of the problems and pitfalls in practice. This presents problems as exceptions to the 'correct' operation of the process. The idealised process is unlikely to be followed in practice.

The literature does acknowledge that the effective implementation of CE processes is not a foregone conclusion – even well-managed organisations may take years to get the basic principles right, which means that they will spend a long time addressing problems in trying to see where they have failed to live up to the ideal process.

This research is based on a longitudinal industrial study over a long period. The relationship framework presents users with the basic assumption that problems will occur and that these can readily be mapped onto the framework so as to show the factors that identify the reasons for them and relate them to the sources of information available to Design to avoid them.

8.2 Integrated product development teams

Teamworking is an essential element of CE. People from different disciplines need to talk with each other, and this should eliminate producibility problems.

The framework can help IPD teams to identify problems. The Producibility Interaction Table can be used as a tool to help structure the discussion, but it still needs a favourable environment. The organisational relationships shown in the framework help to identify problems caused by the working environment, since the IPD team is a form of organisational mechanism. The framework factors can highlight how teams could be structured better, as it draws on CE literature on teamworking, human and cultural to illustrate the factors that can help teams to work. The framework will help pinpoint sources of information that should be brought into the team.

8.3 Producibility

The 'manufacturability' of a part was defined as being equivalent to its 'producibility', and the latter term has been used in this thesis. While the significance of manufacturing cost reduction in the design phase is well understood and accepted, the exact definition of producibility/manufacturability is still very elusive. To measure producibility even after the product is in production relies on subjective judgement, and there are no established ways to measure it.

The list of producibility issues in Section 3.8.3 helps us to understand the context of producibility in the mechanical aerospace components domain. This is a valuable aid to advance understanding of the subject by demonstrating the range, people, processes and skills that are involved in producibility.

8.4 Design

Theoretical studies of design aim to create systematic and idealised models of design activity, but there is little evidence that such models are applied in practice by industry.

The author attempted to generalise the stages of the design process in Table 4.1, and concluded that a generic design model would contain five common stages. Such stages would be readily recognised by engineering managers responsible for organising the design process and its connectivity with the other functions in the project environment. However, the design models tend to have producibility as a constraint to be considered during one or more of these design stages, but without a clear definition of how the constraint should be applied, i.e. what level of producibility information is needed. The framework draws attention to the need for sufficient communication to identify the need for change at the stage when it would have involved minimal effort. It also shows the need for support organisations to be allowed to use time and energy to participate in the crucial up-front work that will benefit them later.

8.5 Manufacturing information requirements for design

Section 4.4 details at length the complexity of the requirement for manufacturing information and various stages of design. The author found that industry practice tended to delay contact between Design and Manufacturing until the design process was well underway. Standard procedures called for producibility inputs to Design, or offered preliminary information to Production, on relatively few occasions. This fell far short of Chen's detailed requirement characteristics, suggesting that potential opportunities to improve producibility were being missed while designers concentrated on aspects such as functionality and performance.

The PI Table was developed to structure the exchange of manufacturing information to give the maximum benefit from cross-functional teamworking. In particular, it sought to address all subjects that might be relevant to producibility at the earliest possible stage, and to keep them under scrutiny until the part successfully entered production. During the SESAME pilot, some of the 13 issues raised were 'textbook' producibility matters, e.g. the rectangular slot, spot faces (AXP S5 and S9). These could have been brought to notice by simple guidelines. However, other issues such as the tooling hole (AXP S3, S8 and S9) would have been extremely difficult to recognise and specify with a manageable set of rules. This showed the advantage of having experienced producibility engineers engaging in direct contact with the designer. The exchange of producibility information is poorly understood by industry, and learning by designers about any shopfloor problems is hampered by the time interval before their design reaches production.

8.6 Sources of information to influence design

Design in aerospace engineering is largely derivative, because the stringent requirements for structural integrity combined with a high-strength/weight performance result in the need for extensive component testing and qualification. These requirements tend to be satisfied by incremental development, and radically new design concepts are rare. Designers rely on previous work and experience as a basis, and seek fresh information only to cover the changes needed to meet a new specification. The aerospace industry develops new products over a timescale of many years, so that the functional specialists on project teams may work on only a very small number of different projects in the course of their careers. The long gestation period means that the accumulation of experience is very slow, and engineers may not have contact with other projects that are meeting problems at the same stage of development so as to share information on the producibility aspects of current production processes.

Although the literature recognises the importance of training for people at all levels and stages of experience in the organisation, in practice the pressures in industry to complete project tasks may prevent an ideal training programme from being implemented. There was little evidence for producibility training being given to designers, who were expected to rely on on-the-job experience. Whatever training may have been received could be out of date within a few years as new production processes were adopted. Recognising those production problems that are related to **training and experience** therefore becomes an important means of making management aware of the need for training or for taking on people with the right experience.

Standards, procedures, specifications, reports and textbooks were a greatly under-utilised source of information, and a potential trap if not properly maintained and managed.

CAD Systems are used to convey design intent and provide a representation for producibility analysis. This is important to support the producibility dialogue, so that the participants can refer to the same design features. However, the cost of a full-function CAD workstation and software, together with its upkeep and the training of users, is very high. This may preclude the provision of compatible fully-featured CAD facilities to all those who could usefully participate in the dialogue from their place of work.

The SESAME pilot project showed how a low-cost viewer would enable a 3D model to be manipulated and interrogated on a PC platform with little or no user training. This could greatly enhance the value of the producibility dialogue for those without CAD workstations, e.g. to allow people on the shopfloor to be involved at an early stage. Whereas the full CAD model may need to undergo translation before it could be viewed on the supplier's workstation or fed into CNC programming, the low-cost viewer used a protocol that would enable files to be readily downloaded from the CAD in a compatible format. However, while the viewer could be extremely useful as an aid to producibility discussions, it had limitations such as not being able to show how the CAD model had been constructed, and it was not sufficiently accurate for quality assurance purposes.

The software for CAD workstations may place constraints on the designer, such as the design sequence and range of features available. It may be difficult or impossible to change features entered early in the design sequence without extensive work to unpick the design. Compatibility/interoperability with other systems may introduce errors or omissions, resulting in queries and delay.

DFM databases and tools often embrace good concepts for producibility and are potentially very helpful, but are frequently under-utilised.

Checklists are cheap, but only can only be expected to identify elementary producibility issues reliably. Even incremental design may generate features that the general checklist does not pick up. Expertise is needed to recognise the impact of changes, and apparently minor differences can push the production process beyond its limits. The implications of checklist questions may not become apparent until they are discussed with those responsible for manufacturing on the shopfloor.

Guidelines can go much further than checklists, but are also historically based and need to feedback from the identification of problems to keep them up-to-date. The impression gained from contact with the aerospace industry was that design guidelines, including producibility, were not prominent as a source of first resort and were not a priority to update.

DFM software was not seen to be used much in the aerospace industry. Much of DFM software was developed for the evaluation of detailed process plans to be used in volume production, and was therefore not of use when considering issues that might involve a change of geometry. Such software would not usually offer redesign suggestions. Designers were more likely to consult the producibility engineer on the team than spend time entering detailed data into a complex DFM calculation.

The author selected 'DFM databases and tools' as a separate category of sources of information for design because of its potential importance in helping to avoid producibility problems. Few factors were found to relate to this category, and these tended to concentrate on their shortcomings. Although much research is being done on virtual manufacturing and knowledge-based engineering, automated producibility has not yet had a major impact on the aerospace industry.

8.7 Communications and Teamworking

Nearly half the producibility factors in the relationship framework are to do with **communication and teamworking**, a much higher proportion than in any other category of sources. No designer works alone to design and make an item in the aerospace industry. Interacting with other members of the team is an important source of information for designers to complement their training and experience as well as the sources of paper and database information, CAD Systems, and DFM software and tools. When the information is not already known, or it is not known where it can readily be found, designers are heavily dependent on communication and teamworking to obtain it.

The relationship framework is a tool that can help narrow the search to identify the particular aspects of communication and teamworking relevant to the type of reason for the problem. This section discusses the significance of communication and teamworking as a source of information and influence in relation to each of the categories of types of reasons, i.e. in relation to the set of factors in each of the tables in Chapter 6.

Human error contains a number of communication and teamworking factors because miscommunication is a common cause of mistakes. These can be particularly significant for producibility when the dialogue is based on wrong assumptions, a question is answered in the wrong context, or errors are repeated because the communication chain did not provide feedback to tell designers there was a problem. In this category, the highest number of factors relate to training and experience, reflecting the prime importance of these in preventing errors. This may also be the effect of assigning responsibility for mistakes to an individual, rather than attributing it to a shortfall in communications: "you failed," not "the team let you down." Communication and teamworking arrangements may not provide an environment where the members are supportive and help each other to avoid mistakes.

Culture and social matters are primarily concerned with the 'soft' aspects of people's relationships with others, so nearly all factors relate to communication and teamworking. Lack of teamwork is itself presented as a type of reason, because of the fundamental importance of teamworking in the producibility dialogue. This enables a number of points concerning leadership and teamwork to be brought out that can help managers in industry to recognise their impact and appreciate that extensive further guidance is available elsewhere. Several factors relate to the rejection of good advice – the 'good' often being recognised only with hindsight – because it is so important for people to examine who had been able to offer the right advice and why it had not been accepted. This is not so that 'witchhunts' may be conducted, but so that managers can realise the importance of the potential contributions from all team members and hence develop teamworking practices that make the most effective use of them. The final factor concerning the need to obtain the best advice may be proved crucial to the survival of the company.

Knowledge was brought out as a separate category to emphasise the importance of factors relating to 'know-how' and knowledge of processes and the environment, rather than including these points in other tables. Failure to recognise the need for advice can result in great embarrassment and delay when problems reach the people on the shopfloor, who cannot understand they were not avoided. Communication and teamworking can do much to promote team knowledge and synergy.

An **organisation** relies heavily on communication and teamworking for its effectiveness. Several factors are included as relating to different aspects of communication as the types of reasons for problems to emphasise the importance of organising the details to ensure the channels are effective. Pressures in industry are such that any barrier to contact may prevent the busy designer or production engineer from seeking or giving advice that is not contractually required. Cost optimisation appears grossly underrepresented in the early stages of design: while being conscious of costs, both designers and production engineers in aerospace would often expect changes in details to be left to a later cost-reduction exercise rather than delay the prototype production. Much space is devoted to metrics and rewards, which are considered vital for developing the right attitudes to focus on what is important for the producibility process to succeed. Similarly, lack of feedback can waste the opportunity to learn vital producibility information. The failure to share information for commercial, political or parochial reasons is an 'own goal' that should recognised and firmly rooted out in any modern organisation in favour of building trust and the longer term relationships.

Teamworking and communication can make a big difference to the anticipation of problems, especially where meetings are properly conducted and organisations ensure that potential difficulties suggested are followed up with a proper investigation, rather than overridden by a dominant chairman or functional specialist. Effective teamworking and leadership can overcome both lack of ability and lack of effort, but for different reasons. Time is often the enemy of producibility, because producibility is not addressed properly in the early stages of design, when people with the right experience on the team could improve matters.

Technical matters will always create their share of problems. There are two aspects relating to communications covered by Table 6.5: the corruption of data, and the need to tell people about actual or potential technical problems. However, the will to communicate is frequently more important than the technical means to do so, and technical difficulties in communication must not be allowed to prevent the producibility message getting through. The main thrust of the communications and teamworking aspects that are related to technical problems is that many technical problems are to be expected, especially where there are changes in manufacturing processes, materials used or design intent. With a high proportion of derivative designs in the aerospace industry, it is particularly important to have such matters clearly visible to everyone involved in the design to manufacture chain so that they may anticipate incompatibilities. It is equally important that they should have a means of communicating their concerns so that technical problems can be dealt with efficiently and the circumstances reported so that they are avoided in the future.

The prime **significance** of the framework lies in the way it can help managers to navigate into these sources of information from the problems.

8.8 Applications of the framework

The whole approach to this research has been concerned with presenting the factors relevant to each category of sources of information or influence so that users can appreciate the significance of the problems they experience in their own environment. Industrial users could map the problems relating to their own circumstances onto the framework, so as to identify the factors and the associated relationships that they should address in order to develop solutions to match their needs.

The aim is for users to be able to map the problems as described in Section 7.1.2, to see which factors could be relevant, then take a critical look at the design-to-manufacture chain to consider how each factor could stimulate action to prevent manufacturing problems reaching the shopfloor.

8.8.1 Risk management

Before a new project starts, the project manager could use the framework to make sure that potential producibility problems are anticipated. During the project, areas where new technology or procedures are introduced can be reviewed with the framework to reduce the risk of producibility problems being introduced.

8.8.2 Problem solving

One of the strengths of the framework is the range of problems represented. This enables it to provide connections between the problems and the reasons for them that can help to identify causes. Bicheno describes **'root cause'** problem solving as fundamental to the philosophies of JIT, lean manufacturing, continuous improvement, the Toyota production system, and TQM (Bicheno 2000) p 130. It means solving problems at the root rather than at the superficial or immediately obvious levels, as described by Wilson et al (Wilson, Dell et al. 1993).

The **'5 Whys'** and the **'5 Hows'** are techniques of problem solving based on the experience of the Toyota Company, who found that 'why' (or 'how') needed to be asked successively five times before the root cause was established. The first reason given should never be accepted, but always probed to expose the underlying causes that led to it (Bicheno 2000) p 130.

Bicheno also refers to a thoughtful article by Finlow-Bates, who concluded that there were no ultimate root causes; rather, root causes were dependent upon the problem owner; there could be more than one potential root cause and the final choice of root cause could not be made until the economics of possible solutions had been considered. There was usually a chain of events that led to any particular unwanted effect, and each person along the chain was not interested in the problems of lower echelons. Each of these causes represented a failure in control or in communication. The real issue was therefore not to find the root cause, but to find how the problem could be solved most economically and effectively to prevent recurrence (Finlow-Bates 1998).

Clarke et al describe how the Theory of Inventive Problem Solving (often referred to by the Russian acronym **TRIZ**) is effected by a combination of the searching process and by the availability of the knowledge required to solve the problem. It applies analytical and knowledge-based tools to enhance the structured generation and utilisation of ideas. TRIZ is intended to improve the effectiveness of the problem solving process and the development of implementable solution concepts (Clarke 1999). L. R. Smith et al provide an example of using TRIZ techniques to answer the question "How do we introduce into an organisation like engineering, the necessary skills and methods so that changes are not needed after the drawings are released?" (Smith, Zlotin et al. 1999).

The framework could assist industrial users to apply techniques such as the '5 Whys' and TRIZ by helping to provide the knowledge required to identify the underlying causes, so as to solve the problems most economically and effectively to prevent recurrence.

8.8.3 Allocation of resources

Industrial resources are always limited, and the framework could help to identify areas where they might be used most effectively. For example, many factors could be avoided by developing communication and teamworking skills to help implement CE.

A training manager could review the factors in the Training and Experience column to see whether the firm's training programmes cover each of the issues with the right people to the appropriate depth and scope. Section 6.4.14.c might lead to the discovery, for example, that no arrangements had been made to brief designers on the consequences of reducing the number of first-tier suppliers. They should be aware that there would be less opportunity for direct contact with the third-party suppliers who actually made the parts on subcontract. The subcontractors' ideas for improving producibility may well get filtered out by the first-tier supplier. It could be useful also to train Procurement and Contracts staff to know when to help bridge the gap by calling on the subcontractors' expertise at the appropriate time to advise Design.

8.8.4 Organisation design

The framework could be used to improve the interface between manufacturing organisation and overall business organisation. The analysis in Section 6.6 showed that DFM success was heavily dependent on communications and teamworking. The organisation strategy should be designed to promote this by considering means such as:

- Metrics and rewards;
- Co-location, representation and meetings strategy;
- Appointment and responsibilities of team leaders;
- Removing contractual, IPR and interdepartmental barriers to teamworking.

For example, Section 6.4.8 contains material covering several different aspects of metrics and rewards. These could be reviewed in the light of a firm's particular industrial goals to ensure that principles such as that of the balanced scorecard are observed. Performance gaps could be identified and timelines set to close them. The performance of a manager of a new project conducting a risk assessment (as suggested in Section 8.8.1) could be measured on how well he anticipates problems.

Sections 6.4.12 and 6.4.13 cover a number of points regarding potential barriers to co-operation. These include the importance of matching the business goals to the needs of the partners on a continuing basis, to avoid being overwhelmed by the complexity of collaboration.

8.8.5 Guideline building

Industrial managers could use the framework to review their particular producibility problems. These could form the basis for them to build guidelines or checklists according to their specific needs and circumstances.

The framework can readily be expanded to incorporate additional factors to cover problems outside the current scope of Chapter 6. This could be done to address manufacturing processes beyond those covered in this research, including those in other industry sectors.

The framework could also be 'customised' for a particular area of application. The problems in that area would first be mapped onto the framework and then used as illustrations as feedback to others in the organisation. If required, factors irrelevant to the application could be précised or removed from the framework to streamline the tool.

8.8.6 Tools development

DFM databases and tools could be acquired or developed to avoid the shortfalls in both the nature and the usage of current material identified in the framework (e.g. Sections 6.4.6 and 6.4.7). Management training should emphasise the potential benefits and encourage the use of tools that are matched to the actual producibility requirements of designers at each stage in the design process.

Chapter 9 Conclusion

This chapter presents the achievements of the research by describing the extent to which the Research Objectives have been met, sets out in detail the justification for claiming that the research makes a contribution to knowledge, and suggests some ideas for future research.

9.1 The extent to which the Research Objectives have been met

This section sets out the extent to which the research objectives in Section 1.4 were met.

Determination of producibility issues

The author generated the list of producibility issues set out in Section 3.8.3 from the experience of the industrial case studies and a preliminary study of the literature, as described in Chapter 3. They represent the issues of concern to current practitioners in the research domain, i.e. the design for manufacture process covering mechanical piece parts for the aerospace industry. This list provided a valuable basis for focusing the research on producibility matters of practical relevance.

The types of reasons for problems and their concept categories were similarly generated, as described in Chapter 5, following the author's immersion in the industrial case studies. Together with the list of problems and opportunities, this provided a full response to the requirement to determine producibility issues.

Identification of sources of information and influence

The set of five concept categories for sources of information and influence was developed primarily from the literature set out in Section 4.5, as described in Chapter 5. They included 'CAD Systems' and 'DFM Databases and Tools' as separate categories to help draw attention to factors relevant to these areas. 'Communications and Teamworking' completed the closed set by ensuring that any information not found from the other four categories could be made available in this way. In addition to providing factual information, each category was capable of influencing the designer in matters affecting producibility.

The assumption was made that the information available to prevent any particular manufacturing problem was available somewhere, in some form, tacit or explicit. If this information were not already written down, on an electronic database, or in someone's head, then the lack of it could be recognised and research or tests put in hand to find answers in time for them to be used in the design process. Given that producibility information was available that would enable the designer to alter the design so as to avoid manufacturing problems before manufacturing instructions reached the shopfloor, then it was assumed that this information could become known to the designer through one or more of the sources.

These five categories provided a full response to the requirement to identify information sources and influences in the research domain.

Framework for application to practical engineering environments

The Relationship Framework set out in Chapter 6 was developed as a means of setting out the answer to the Research Question "Why do manufacturing problems reach the shopfloor when sources of information are available to prevent them?" in a form that could be of use in a practical engineering environment to help managers find factors that related to their own problems and diagnose their sources. These factors could either prevent the designer from identifying, receiving or knowing of the information needed to avoid a producibility problem, or they may influence the designer who knew the information to fail to apply it so as to overcome the problem.

The author contends that breadth of the database assembled from industry and from the literature, and the way that the framework was developed and organised to present the relationship factors derived from the data provides a comprehensive answer to the question of why such problems reach the shopfloor. This fully meets the requirement to devise a framework for application to practical engineering environments.

Partial validation of framework

The reseach objective was limited to partial validation because it was not practicable in the time available to test the framework in industry after it had been developed. The following paragraphs set out the aspects of the work that the author blieves justify the claim that partial validation has been achieved.

The recommended tests for research validity were set out in Section 2.7 Table 2.2, together with details of the research strategy adopted to satisfy them. The author contends that the best practice and industrial case studies provided an accurate picture of the industrial problems by using the rich communication methods of semi-structured interviews with each participant in the DFM chain, followed by face-to-face review meetings covering all of the 38 producibility issues from the industrial case studies.

A cross-section of the aerospace industry reseach domain was obtained by the use of live case studies from both Defence and Civil Aerospace involving four major UK companies –two as customers responsible for design, and two as manufacturing suppliers. The manufactured mechanical piece parts covered were made from stainless steel, aluminium, titanium and composites involving a variety of processes. In each case the author visited the manufacturing shop floor as well as the design, quality and purchasing offices, to ensure that the practical working environment was fully understood. A wide range of literature was studied to to support the industrial experience and provide further material for populating the framework. Both the literature and the best practice study were drawn from a much broader field, but provided much material that was agreed by practitioners to be relevant to aerospace. It is reasonable to infer that many of the entries in the relationship tables are generalisable to a range of industries.

Chapter 7 showed how the 38 producibility issues could be mapped onto the relationship tables that formed the framework, and also explained the grounds for believing that the framework had industrial validity, satisfying the practical relevance tests of Section 2.7 Table 2.3.

9.2 Justification for the contribution to knowledge claimed

The output of this research is the completed relationship framework set out in Chapter 6. In order to develop this framework, the methodology described in Chapter 2 was designed. The initial steps in the methodology involved teamworking on the AEROEXTN Project. The author does not claim total credit for the data gathered from industry as a joint effort. The author did, however, take the lead in developing the Producibility Interaction model described in Chapter 3. He also gathered and documented the data from the civil aerospace studies, and used the combined set of industrial data together with his study of the literature as the basis from which to develop the framework.

The first use of the data was to explore the context of producibility in the mechanical aerospace components domain, so as to develop the list of producibility issues listed in Section 3.8.3. As a means of helping the understanding of 'producibility' in this context, this represents a contribution to knowledge.

The process set out in Section 5.2 for formulating and categorising the lists of types of reasons and sources of producibility information and influence was fundamental in filtering the large volume of information to develop the framework structure into which the relationship factors could subsequently be entered. The concept of using a two-dimensional matrix as a framework for presenting qualitative research results is well established. However, the author claims that the recognition of the practical relevance to producibility of the types of reasons, at a level of granularity that enabled the identification of factors to relate them to the categories of sources, represents a contribution to knowledge.

The concept of a closed set is well known. What is novel is its application to defining the sources of information available to designers as a closed set such that, given that the information was available somewhere, one or more of the source categories defined must be related to each of the types of reasons for producibility problems. This was the key to the use of the framework in building the answer to the Research Question, enabling each of the factors to be identified from the large volume of problem issues from industrial experience and literature. Entering the factor into a cell immediately showed its relationship both to its type of reason for causing a problem and to the source of information that could influence design. The ability of the framework to 'pigeonhole' any new factor suggested by scrutiny of the database was a major benefit in enabling the framework to be populated rapidly. This was especially useful when new material was found in the literature, because it could be entered directly into the framework without going through an intermediate process of collating it with like items – the framework effectively acted as a collator.

The completed Relationship Framework is a diagnostic tool that is not available in the published literature. It has been compiled with a very large element of industrial experience that fully recognises the responsibilities and concerns of managers, so that they should be able to relate readily to the factors and identify them with their own experience. At the same time, the broad basis of the literature consulted enables the table to show factors covering embarrassing problems, such as those resulting from human error or personal antagonism. Managers are reluctant to admit to these, and would most certainly avoid putting them in project reports.

9.3 Ideas for future research

Application of framework to industry

The research timescale did not allow the framework be tested in industry. Further research could demonstrate its utility, to refine the factors and provide additional illustrations of their application.

The framework could readily be extended to other industrial contexts. The methodology that was affected in developing this framework could cover other industries and be applied to other fields. Many of the types of reasons for problems would read across directly to other applications, with a change of wording to adapt to the contexts. Five categories of types of reasons could well be unchanged, since they have general applicability, e.g. 'organisation'. Sources of information would have to be categorised according to the specialist function, but 'training and experience' and 'communication and teamworking' could be unchanged. The framework could then be populated with factors that related to the nature of the business concerned, but again many factors are likely to be common.

Involvement of industrial psychologists

The framework represents an engineer's attempt to relate problems and lost opportunities in producibility to the reasons for them and the sources of information to avoid them. The contents of the framework has a very high proportion of 'soft' factors, in terms of both training and experience as well as communication and teamworking. Even in the other three source categories one may argue that **how** people use the information is more important than the **availability** of the information. Although the framework is a practical tool to enable managers to home in on improvement actions or plans to understand fully the reasons why producibility problems occur, industrial psychologists could help to develop a further understanding of the human factors involved.

Business process re-engineering

Hammer and Champy show the importance of following the business process rather than attending to narrowly defined tasks and working within predefined organisational boundaries, emphasising the importance of information technology acting as a neighbour to allow organisations to working radically different ways (Hammer and Champy 2001) p 50.

Further research could develop the framework to assist directly in the radical re-engineering of business processes in the design-to-manufacture chain.

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Appendices

A. **'Best Practice' Study**

B. **AEROEXTN Project**

C. **Communication of Producibility with Design (the PI Table)**

D. **Civil Aerospace Studies**

E. **Report Proformas**

Appendix A Best Practice Study

(See Chapter 2 Section 2.9.1 and Chapter 3 Section 3.2.3)

A.1 PRODUCT REQUIREMENTS

	Aircraft (1) **Customer/ Supplier**	**Telecoms (T) & Consumer Electronics (E)**	**Aircraft (2)** **Civil & Military**	**Automotive** **Component Supplier**	**Automotive** **Car Manufacturer**	**Discussion**
Annual sales volume	Total production planned: 250-300 x 2 engine nacelles 3000 parts each	5000+ per product (T) 200 000 TV (E) per model	Hundreds of each type of engine (RR) Boeing: 300 Airbus: 126 delivered, 8.8Bn turnover(1996)	2M shafts, 490k for one customer £140M/year: 34% global market for these components 60k vehicle sets/yr/model	Millions (typical)	Design re-use? Yes. Also standard floor mountings and modular jigs allow shop-floor flexibility and low-cost production re-runs
Typical cost range	Nacelles: Tooling £5-6m Production £0.75m each	Tooling £0.5 m Production: Several £k each (T) Several £100 each (E)	$100 to 200m each aircraft £5m per engine Major engine component: tooling $1m; production £70-80k per item Aircraft A wings: £98m for 23 ac sets	Half-shaft £70 Tooling £250k/vehicle	£7 - 30k for car	
Major sales driver	Performance, cost and reputation	Performance, cost and reputation	Politics, performance, cost and reputation	Performance, cost and reputation	Styling Performance Cost Brand	

Frequency of new projects	12-18 months	(E) - several new models per year (T) - 18-24 months	Every 2 years for each manufacturer	Several/yr, each tuned to particular vehicle. Technology path: new range of 7 standard sizes being developed 1996-2001	Every 2 years	Intro-to-manu time for aerospace was questioned. We need to clarify frequency of introduction, as opposed to time taken from concept to manu.
Operating Environment	Aircraft -55 to +70C	Consumer: benign home/office Road side/mobile: more rugged Military telecomms: very rugged	Military: very wide range of conditions to be met	As for vehicle Note: Group Research developed own lubricants to cope with extreme conditions. Now adopting thermoplastic boots instead of rubber	Outdoors - worldwide -20 to +50C	
Shelf life before use	Not usually significant	Not usually significant	Military: a proportion of aircraft may be stored as fleet reserves	Not usually significant	Storage before sale to be considered	
Life cycle support requirements	Inspect for structural integrity and repair as necessary over 20+ years	Life-of-type spares held for 3 - 7 years	15-80 years Support cost per flight hour	10 yrs+	10 yrs component support 3 yrs warranty Minimum maintenance	
Reliability characteristics	Critical parts designed for safe life or failure-tolerance	High MTBF	High despatch reliability/military mission availability	Highly developed and tested. Greatest threat to reliable operation is damaged boot allowing contamination	Looking for zero warranty claims Component target (10 parts per million)	

Legislation/certification requirements	JAR/National airworthiness requirements	Electrical safety, electromagnetic compatibility, consumer law	JAR/National airworthiness requirements / Military standards and tests		Construction-and-use regulations, including crash-worthiness	One supplier said EMC legislation had facilitated their involvement in the design cycle.
Technological risk of machined CAD intensive parts	Proven technology for current project	Innovation - medium to high risk	Medium-high risk	Low risk	Low risk	

A.2 ENGINEERING CAPABILITY & SKILLS

	Aircraft (1) **Customer/ Supplier**	**Telecoms (T) & Consumer Electronics (E)**	**Aircraft (2)** **Civil & Military** **Gemeral**	**Automotive** **Component Supplier**	**Automotive** **Car Manufacturer**	**Discussion**
R&D	Research focused 2 products ahead	Current products designed using research of 4 yrs ago	Military research: DERA, Govt-funded, some PV	Group has 4 global R&D centres- UK Germany US & Japan	Own R&D in Japan - tending now to rely on suppliers' R&D	
Manufacturing eng **-Producibility - ownership & location**	Depended on product	Design owned, or Customer (assembler) owned, or Supplier owned	Aircraft A Supplier owned - skills based	Expertise of shop-floor based manuf/process engineers available to customer-focused business units	Suppliers manufacture, deliver to site, and sometimes fit. Very advanced	In the New Product Definition stage, producibility people are needed on-site at Customer

Cost control **Supplier/ customer**	Cost design accurately No design-to cost-yet	Suppliers tasked with cost reduction Tracked by Procurement from early design		Target costs set by customer and agreed. Suppliers required to reduce cost in production year-on-year	Target costs set and agreed with suppliers, who are required to reduce cost in production year-on-year	Costing what-ifs can be built into Pro-Eng. UPC targets are set at MBUK.A reqt for year-on-year cost reduction could lead to suppliers inflating contract prices.
Supplier IT currency, design support & automation	Yes	Yes; however, level of use varies: (E) suppliers have CAD access but do not always use it at their site, although they do have guest engineers resident on the (E) site. (E) supplier is IT current enough to finish designs at their site	Aircraft A - poor currency; CAD current guest engineers with Prime; Producibility at supplier don't use often and lose. Suppliers may sub-contract IT aspects	Unigraphics changing to Pro-Eng for of this Group. Some customers now require supplier to adopt native CAD eg: Ford C3P IDEAS, Honda CATIA, Rover CADDS 5	Guest engineers from key suppliers	Knowing Supplier capability is an issue for Customer. The idea of 'use it or lose it' was agreed to apply to CAD proficiency.
Training & qualification	CAD training contracted out, to centre in town Rely on experience for cross-functional skills			Training programme for CAD modellers to ensure common approach	Mgt training scheme. KT problem-solving course. Designers spend time on shop floor. Workers have 2 weeks training on floor	

A.3 DESIGN PROCESSES

	Aircraft (1) **Customer/ Supplier**	**Telecoms (T) & Consumer Electronics (E)**	**Aircraft (2)** **Civil & Military**	**Automotive** **Component Supplier**	**Automotive** **Car Manufacturer**	**Discussion**
Cycle time	4 Yrs (Goal is 2 1/2yrs)	10 months UK 6 months Japan	RR 4 yrs (goal 27 months) Boeing 8-9 yrs to 4 - 5 yrs Airbus similar	150 weeks RFQ to SOP	31 months	
No of people involved	600	(T) 40	Company B 630 Boeing 4000-5000 design engineers for project. Airbus similar	26, incl 6 draughtsmen	400 design eng in UK for new and update work.0 (8000 + in Japan)	
Start & end points	ITP to EIS	ITP to EIS	Concept options to manufacturing definition	RFQ to SOP+10 weeks	Concept sheet to start of production	
Design phases	Concept, Joint development and detail	5 steps	Company B IPD has 7 phases of product maturity (Military - Entry-to-Service)	Total of 6 weeks' design during 150 week cycle	Typically 7	
Ownership of process	Customer owns product-engineering system. Risk Sharing	(T) Owned by customer (E) try to empower suppliers; default is their Engineering Head	Boeing own major design processes and monitor on site. Company A - project leader owns process	Business Unit	Suppliers all responsible for tooling	

Design specification/ Design ethos	Detailed spec generated during Joint Development Phase	Gate processes set key parameters Designers work closely with suppliers	Prime often dictates much of detailed design, Moving towards sharing	Prime dictates interface spec/system requirements and geometry	Suppliers agree spec	'The ability to demand flexibility with suppliers comes with volume product' applied to late specs to suppliers. Customer took the purest view of gates: no pass unless all gate deliverables are met.
Design for manufacture	Main suppliers involved in concept and responsible for detailed design	Weighty assembly influence - supplier input high, suppliers in at concept	Prime's manufacturing engineering department signs off design	Weekly meetings with cross-functional team address commercial feasibility, costing, capacity, & production capability	Reduce parts count by focused sub-group	Problem with discussion of early model spec at Customer is that Config Control system is geared to drawings (somewhat later); PDM internal to CAD deals with early changes to models - no supplier access.
Risk analysis	Impact examiner as process - Has been poor in the past: aim to improve	(T) - Business Units responsible - based on review	RR - Formal risk assessment meetings. critical components heavily analysed	Investment risk on capacity may be taken before production tooling order received 60 weeks before SOP	FMEA (not computer led)	

Design release	Gate process in BES	(T) - Gate process	IPD gate process- BAe Airbus process	Prototype SOP-120 Production SOP-60 Late changes to meet customer NVH tuning	Formal gates with countermeasure plans	
Sign-off authority/ Change control	Major partners have authority in own area	Parts to pre-determined signatories cross functional	Boeing DBT - department Airbus - mainly Des. Both sign. Now D+M		Paper drawings signed Eng/Sen Eng/Mgr/Car manufacturer	See above. Major changes affect critical design elements; minor affect the rest.
Design build teams	Used in Joint Development Phase - involve all major partners	Use of project teams includes all players (suppliers too) from concept onwards	Boeing BAe Airbus DBT all functions generally inc. suppliers	All operations controlled by business units: sales, design, eng, applicn, conformance(quality)	By area + trial production	
Project schedule awareness	Progress reviewed at check meetings	Regular project meetings; (E) daily or weekly; things to do list	Airbus - fixed targets for everything. BAe MA&A: IPD goal is 50% reduction in time and 100% achievement of target dates	Very conscious of schedule	Very conscious of master schedule and sub schedule	
Cost awareness	Aim to design to cost Joint Development Phase major parts cost	Designers own costs	BAe MA&A: IPD goal is 30% reduction in cost	Very much aware	Very much aware - pressure to reduce costs year on year - lean production	UPC targets are set by Customer

Design history	Trade-off studies on paper : will be on-line	(T) - Live project file on server records actions and reasons	BAe Filton: CADDS 5 keeps 5 editions live, and archives all iterations	Because now no functional centres of excellence, named individuals hold "design custodianships"	Past problems from lack of written record in Japan. Suppliers expected to keep design info.	Is reading design history files compulsory? No - design/decision history is simply made available. Noted that history of items **not** made is rarely kept.
Change control	All configuration details captured and retained on DB Some local empowerment	Automated sign-off, pre-determined signatories	BAe Airbus have centralised control	Paper system	Paper system - very few changes in production (except for cost reduction, safety and face lift)	Japanese view of 'no change once in production' was of interest
Physical Modelling	Some details modelled	Stereolithography	RR produce external physical model for pipes/cables/components - also used for training	No	clay models	Models can be soft (CAD) or hard (physical). To Customer 'soft' models include alternative-material hard models. Could be used for 'Haynes Manual' approach to producing manu information, also for deciding external servicing.
Prototyping	no physical prototype	May produce up to 30 examples from soft tooling for trials	RR CAD models each prototype including test instruments	Prototype order release at SOP-120. Customer may double or triple source at this stage	4 Prototypes - key builds (including crash & vibration tests) + 2 engine, 1 body, 1 underfloor	

Tooling	Supplier owned	Soft tooling for development, hard for production. (T) tooling budget controlled by producibility man. Some tooling Supplier owned.	Supplier owned, constrained by budget	Usually paid for in stages by supplier. May be idle for 50 weeks between pre-prod delivery of 20-30 sets with 'off' tools and SOP	Body tooling by Car manufacturer in Japan - aim at production tooling first time	

A.4 IT ENABLERS: DESIGN/SUPPLIER INTERFACE

	Aircraft (1) **Customer/ Supplier**	**Telecoms (T) & Consumer Electronics (E)**	**Aircraft (2)** **Civil & Military**	**Automotive** **Component Supplier**	**Automotive** **Car Manufacturer**	**Discussion**
Communications facilities	Transatlantic links Voice e-mail Teleconferencing	Comprehensive network	Links between major sites e-mail fax/telephone		e-mail (this year) telephone, standard documentation, video-conferencing	All recognised a reluctance to use videoconferencing; possibly because of lack of physical presence & absence of body language. All agreed vid-conf better than no meeting at all.

CADCAM	CATIA for customer CADDS5 for suppliers EIS provides management info to common snapshot	Pro/Engineer CAM link to suppliers, common CAD, although supplier usage questionable. Eg Supplier 'finishing designs'	RR CADDS5 to CATIA uses STEP AP203 for engine mounting points and interface	Unigraphics changing to Pro-Eng for all GKN with H-S in lead. Some customers now require supplier to adopt native CAD eg: Ford C3P IDEAS, Honda CATIA, Rover CADDS 5	Car manufacturer's own system - sometimes difficult to interface with others, but some contractors insist on using CATIA to avoid losing CATIA skills	Boeing has made STEP a mandatory condition of contract. How does Car manufacturer deal with suppliers who retain CATIA skills? Answer - Car manufacturer still heavily dependent on paper as default
Remote product data link	High-capacity link across Atlantic	(T) full	Many systems in use. Boeing have link across Pacific to Japanese suppliers	Link to Ford being set up. Others may follow		Aircraft (1) had just started a 5-year plan to develop a common PDM system
Programme information	Supplier/Customer kept fully informed schedule harmonisation meetings - slippage declared and rectified. Management info system takes snapshot for executives to use common baseline data for programme management meetings	Open & on-line project managed; disseminated to tasks.		New control /info system being adopted for Group	Rigid programme - paper system - demanding but respected	Some discussion about design ethos here too. The idea of 'baring your chest' - volunteering problems & highlighting early slippage for communal recovery effort

Design information - availability to suppliers	Yes - available as required for specific requests, bulk updating overnight to maintain current model. Cost/ weight information on line as design evolves. Suppliers pull/ Customer push	Suppliers can log in with access card and pull info off controlled server	RR supplies model geometry for pipes and cable forms on floppy disk - no longer produce master jigs	Model information becoming available, but paper still master	Most suppliers use 2D paper drawings - all through design admin office	Some general interest in the idea of access cards for security access for suppliers. Note: Link BAe, the exec level intranet already uses this system.
Specification changes	Eng Ch Mgt Systems	On line	electronic paper	Paper	Formal procedure paper-based - aiming to reduce changes after gate point by 80%	Long discussion re who carries blame for 'grey-areas', eg that which falls between what is communicated, what is interpreted, & what is inferred. Supplier learning is important to cultivate - although learning may be faster when faults cost the supplier.
Parts ordering/ Access to up-to-date BOM	Electronic BOM	(T) have SUMMIT integrating new designs with MRP tools	Electronic BOM	Electronic BOM	Efficient electronic JIT supply - best in Europe	

A.5 SUPPLIER RELATIONSHIPS

	Aircraft (1) Customer/ Supplier	Telecoms (T) & Consumer Electronics (E)	Aircraft (2) Civil & Military	Automotive Component Supplier	Automotive Car Manufacturer	Discussion
Contract		Overall Supply Terms & Conditions. Moving from semi-custom design agreements due to time-to-market reduction No formal agreements on relationships		Still in competition for much of business until customer chooses from multiple-sourced prototypes		
Strategic partners	**Selection:** Strategic decision **Role: cost & risk sharing** **Responsibility :** major structure & systems **Participation in design:** Joint Definition & Development **Tooling:** Invests & owns tooling	(T) - parts of own organisation Suppliers of a cross-section of commodities -range -joint development -joint marketing	Airbus - varies - changing to autonomous Airbus corporate entity. Boeing - evolving cost and risk sharing - still under technical direction of Boeing engineers	Would like to be involved in total drive train system design from concept, but auto industry secrecy normally prevents any contact until SOP-150 weeks on 5-yr project	Dependant on strategic suppliers. Moving to Commodity Group strategic importance	Apparent mismatch between Supplier's partner relationship and requirement to go through a competitive tender loop was explained by Customer's contractual obligation to go to competitive tender for all parts

Preferred suppliers	**Selection:** by invitation **Role:** major assemblies **Responsibility :** specific area **Participation in design:** detail **Tooling:** invests, owns	Preferred suppliers audited on performance	Selection: competitive tender on outline design, coupled with experience from any previous contracts Airbus - owns tooling and eng package	Once prototype selected for particular vehicle, H-S may direct production to optimum geographic location (eg parts for Ford may be spread 20% in each of several sites). Car manufacturer still require single plant	Supplier rating - quality/cost/ SAIS measurement Design/manufacturing Dual source all components to tender	Some concern expressed that 'installed cost of components' often not recognised, hence real cost of choosing particular supply route not visible. Lack of 'Value Engineering' - eg implied terms in specs could be missed and add time & cost to the supply process.
Subcontractors/ vendors	**Selection:** price/performance **Responsibility :** individual parts **Standard items,** Nil **Participation in design** **Tooling**: Amortised in price	(T): Central global contract awarded a nnually for piece parts Niche companies ('mesh globalisation')	Airbus - own tooling for non-standard parts	'GLOCAL' organisation has own steel supply for each continent		
Sub-suppliers network mgt	Suppliers empowered to manage sub-network		Varies			Long lead-time items need to be visible to the Prime early in the design process.

Enforced suppliers	Rare	Local agents of global suppliers	Political offsets		Some items from Japan for raw materials/ big 5	Very relevant to Customer JV. Incidences of enforced suppliers include being forced to work with a competitor, and sole source suppliers.
Proportion of outsourcing			Airbus - 70% of volume	Related work with plants in group	70% body tooling from Japan	

A.6 INTELLECTUAL PROPERTY RIGHTS

	Aircraft (1) **Customer/ Supplier**	**Telecoms (T) & Consumer Electronics (E)**	**Aircraft (2)** **Civil & Military**	**Automotive** **Component Supplier**	**Automotive** **Car Manufacturer**	**Discussion**
Ownership		Concepts patented. Design agreements for components - IPR sensitivity known/ managed. Non-disclosure or informal agreements	Company B: IPR owned for anything "having a uniqueness"	Own IPR for the components they supply to a number of customers		IPR for Company B rests at Plc level
Supplier processes	Supplier's IPR protected subject to customer's designer integrity	Supplier's IPR protected subject to customer's designer integrity	Supplier's IPR protected subject to customer's designer integrity	Some concern that sharing certain CAD systems could enable customers to reverse-engineer components		Suppliers could be vulnerable, despite non-disclosure agreements, to a prime's designer indicating to a rival supplier that there were better methods of producing a part.

A.7 Metrics

- Time to Market - definition of start and end points - seen by the Group as very important metric.
- Number of Design Queries - not seen as important, compared with their cost. 30 to 40% of design queries in aerospace cover missing dimensions on 2-D paper drawings.
- Number of Design Changes - important only after design freeze.
- Cost of Design Changes - design effort, tooling changes, wasted materials, delay.

Abbreviation	**Meaning**
BOM	Bill of materials
CAD	Computer aided design
CADDS 5	High level CAD software by Computervision (now part of Parametric Technologies)
CATIA	High level CAD software by Dassault Systèmes
EIS	Engineering information system; Entry into service
IPD	Integrated project development; Integrated product development
IPR	Intellectual property rights
ITP	Instruction to proceed
JV	Joint venture
MTBF	Mean time between failures; Mean time before failure
PDM	Product data management; Product document management
PLC	Public liability company
RFQ	Request for quotation

SOP	Start of production
STEP	Standard for the exchange of product model data (ISO 10303)
UPC	Unit production cost

A.8 Observations

The following general observations from the study were found helpful in appreciating how the design-for-manufacture chain operated in practice, and in shaping the approach for the remainder of the research programme:

- Various levels of suppliers' integration existed, from full risk-sharing partnership to third-tier (no design content) supplier involvement.
- Product/industry specific considerations could be significant. Aerospace components tend to be produced in hundreds over a period of years, and production was subject to frequent upgrades or modifications. By contrast, the mechanical parts of a television set may have a production run of 200,000 over 6 months, and any changes were likely to be incorporated into a later model rather than by altering the current product standard.
- Procurement/commercial practices were a constraint, but easing as contractors recognised the advantage of co-operating in a spirit of mutual trust. This was likely to yield greater benefits than adopting a confrontational approach, where all work was subject to detailed contracts so that the slightest deviation could lead to litigation.
- CE implementation was through trial & error. Although there are many prescriptive methods, none contained the level of details to guarantee that CE will work.
- IT, including CAD/CAM, was readily available but not always used effectively. Often hardware 'solutions' were installed without a clear plan of how they would support the business processes. Unless a CAD workstation operator applied himself regularly to using a complex software package, he would rapidly lose the skill to do so ('use it or lose it').
- Capability was not equivalent to history. Suppliers would like to be asked whether they could do other things, rather than be judged solely on past performance. However, experience of unfulfilled promises for new processes highlighted the importance of process proving, involving realistic trials, testing and evaluation.
- Cultural change was essential. Leadership was a very important aspect of getting people to work together for the benefit of the whole enterprise, rather than for the optimisation of their own particular function.

Appendix B AEROEXTN Project

B.1 Context

The AEROEXTN project was set up to develop processes by which competence in concurrent engineering could be applied to the Extended Enterprise. This involved the design-to-manufacture chain from the customer (responsible for design, assembly and test) to the supplier (responsible for the manufacture of machined parts, on a remote site). The supplier would be involved in the design loop at an early stage, providing advice on Producibility. This arrangement is referred to as 'supplier in the loop' (SIL) working, or 'early supplier involvement' (ESI), and is illustrated in Figure B.1.

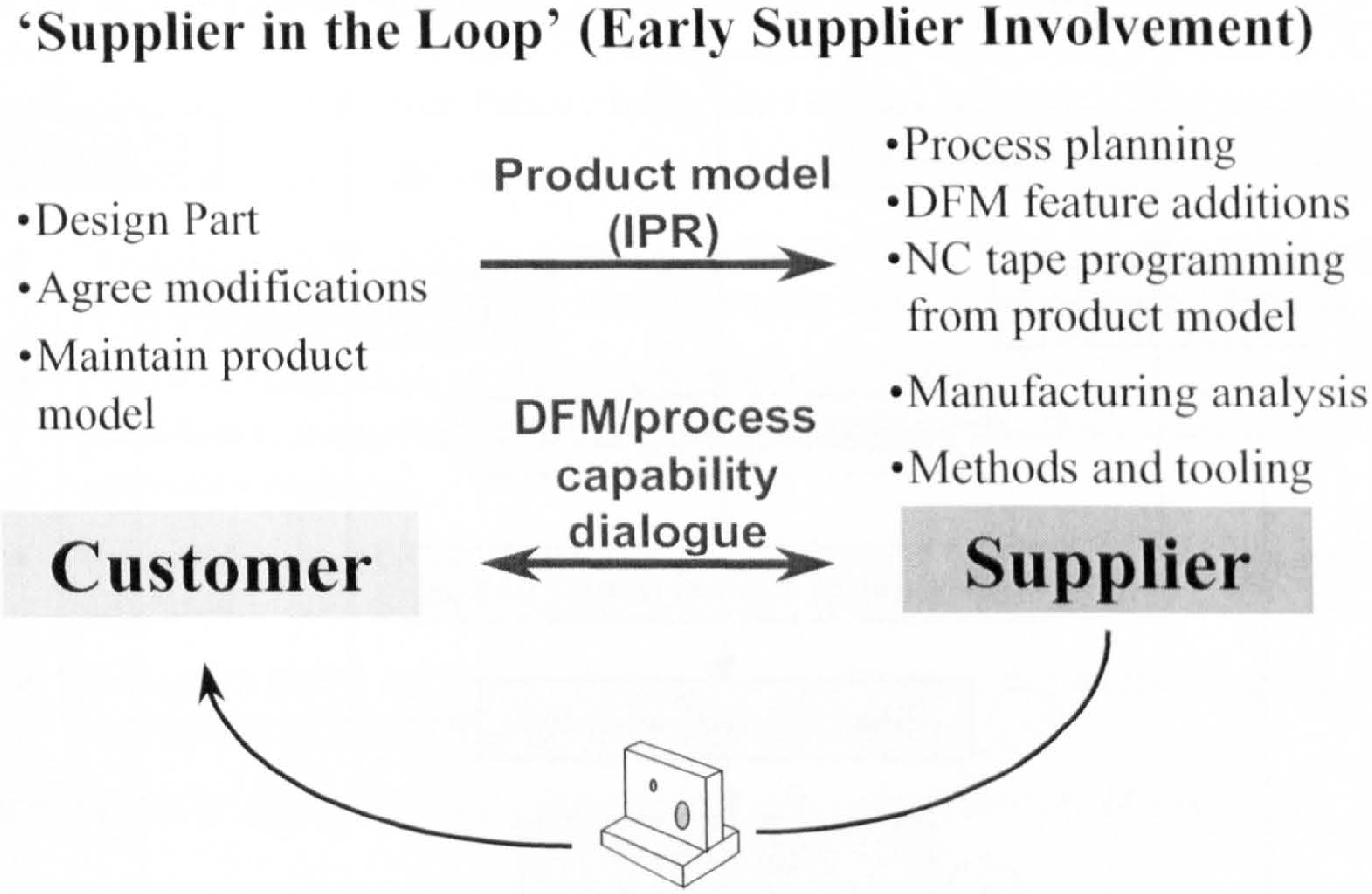

Figure B.1 Supplier in the Loop Concurrent Engineering (SIL-CE)

B.2 Project structure

The AEROEXTN Project structure and flow chart are shown in Figure B.2, which is annotated with the numbers 1 to 7 to indicate the items of particular relevance to this thesis, corresponding to the methodology actions steps described in Sections 2.8 and 2.9.

The project ran from June 1997 until September 1999, and was managed by senior academic staff from Cranfield University (Dr Ip-Shing Fan) and the University of Luton (Professor David Hamblin) as Principal Investigators. Mrs Elly Philpott, of the University of Luton, and the author were employed as full-time researchers for the project.

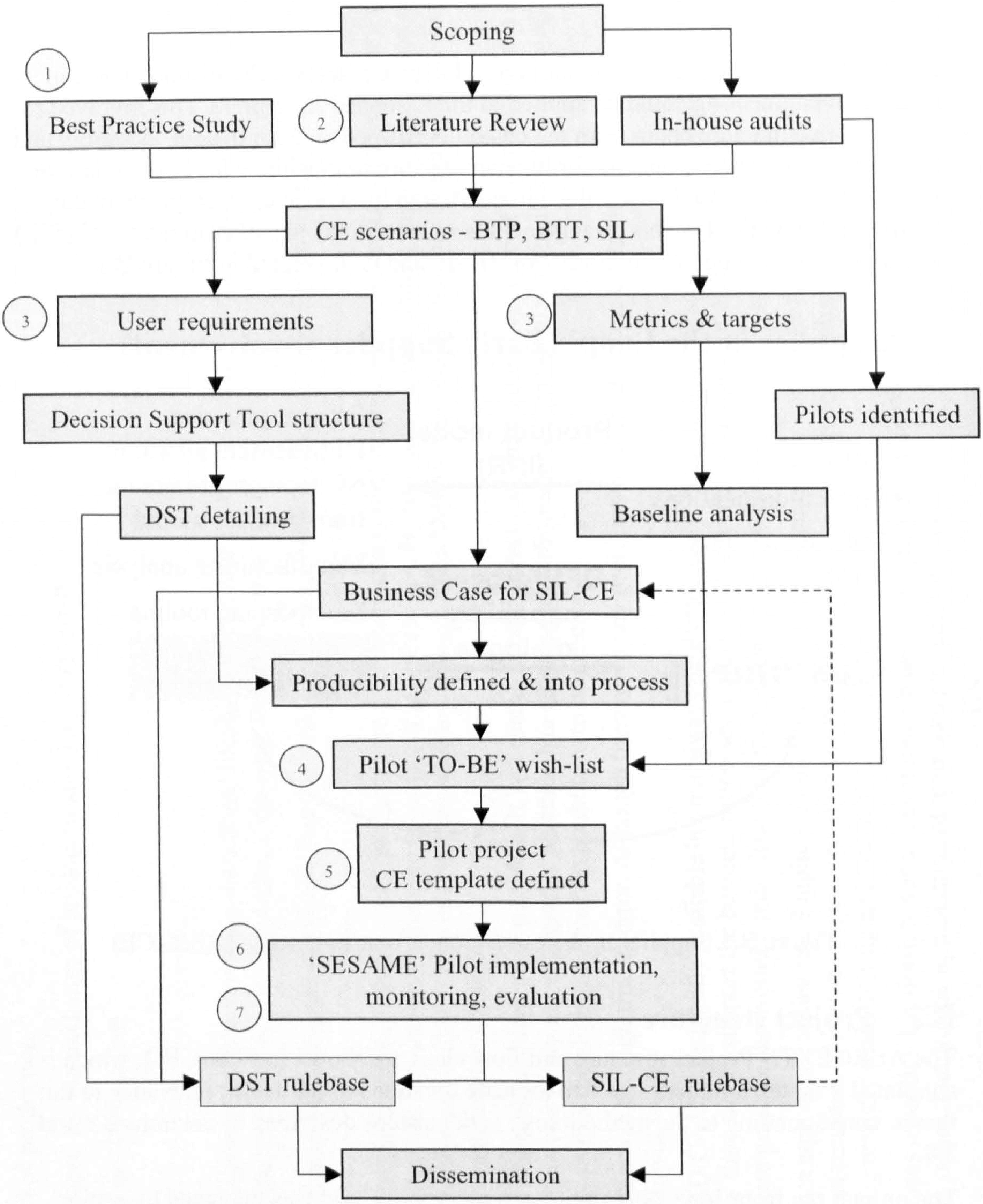

Figure B.2 AEROEXTN Project structure and flow chart

B.3 Prescriptive CE implementation model

B.3.1 CE Implementation template

The AEROEXTN team used the prioritised list of issues and enablers derived from workshops with industrial collaborators as a basis for formulating a list of implementation tasks to plan the involvement of the supplier in the design stage for SIL-CE working. These 'TO-BE' tasks were derived from comparing the current 'AS-IS' processes with the arrangements needed for the supplier to contribute production-engineering expertise.

A planning structure was needed for the AEROEXTN live pilot project, in order to implement the 'TO-BE' tasks in the appropriate sequence. It was important that long-lead items and pre-pilot tasks were put in hand in good time to be completed before the start of the pilot phase. A number of Producibility activities were planned around the core requirement to facilitate Producibility Interactions between customer and supplier.

These implementation tasks covered:

- Long-lead items, such as developing the producibility process, obtaining management buy-in for the business case, and choosing the pilot parts;
- Pre-pilot tasks, such as auditing the present design and manufacturing processes, addressing contracts and intellectual property rights (IPR), and arranging any necessary training;
- Pilot tasks, such as producibility interactions, programme management, culture alignment, communication, and measurement;
- Post-pilot tasks, such as analysing lessons learned and addressing the digestion and re-use of knowledge.

The template in Figure B.3 was developed to illustrate the flow of tasks.

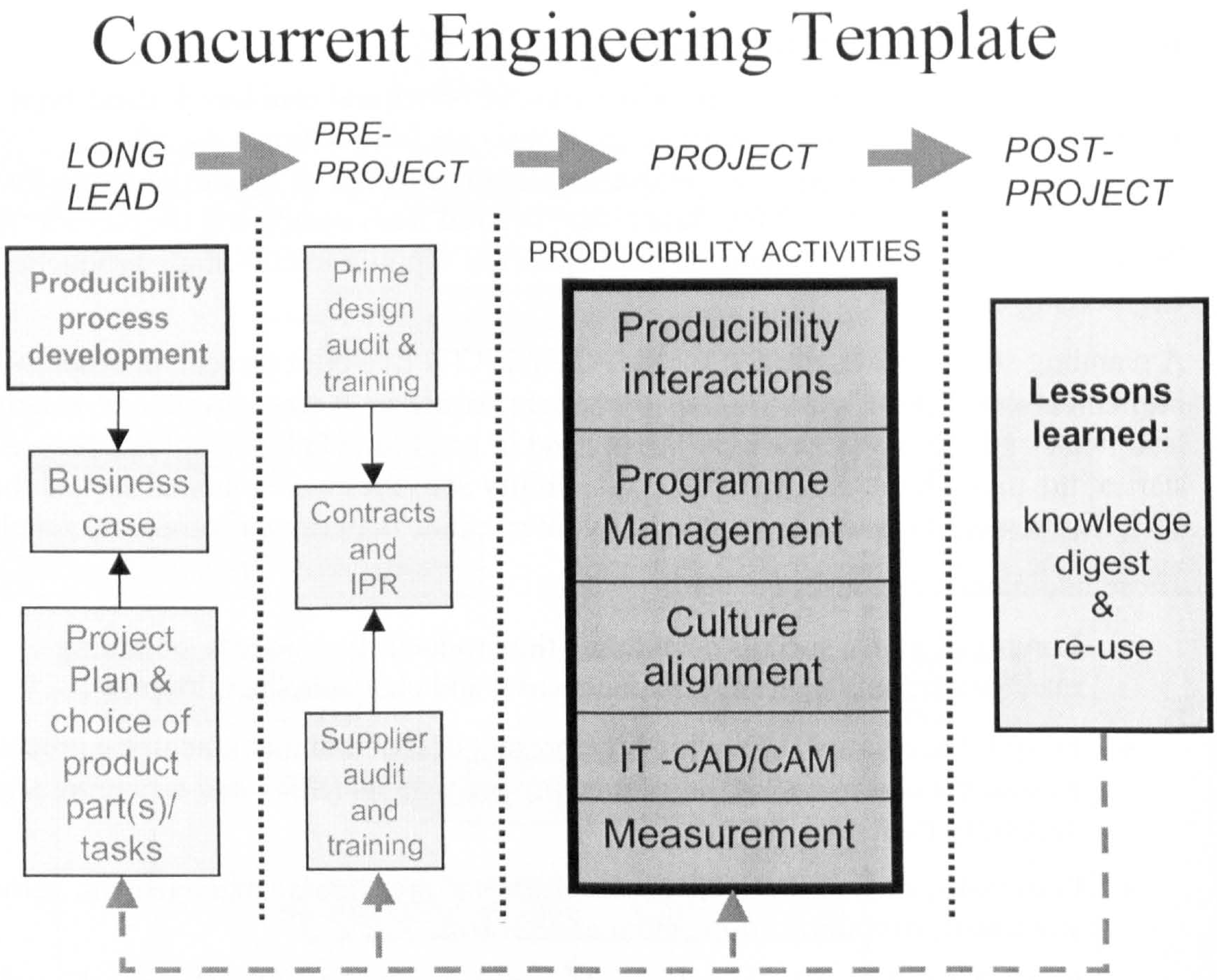

Figure B.3 Block Schematic CE Template

B.4 SESAME

B.4.1 Purpose

The purpose of the project named 'SESAME' was to pilot CE in the Extended Enterprise on a live project. A co-operative independent supplier produced complex mechanical parts designed by a prime contractor. There was no sub-contracting of design work to the supplier. The researchers facilitated the setting up of a team to bring the designers together with the supplier's producibility engineers at an early stage of product development.

B.4.2 Pilot Project Circumstances

The SESAME industrial circumstances were as follows:

- The customer was a Defence Original Equipment Manufacturer (OEM), who had recently outsourced the manufacture of machined parts, retaining design, assembly, systems integration and test;
- The supplier undertook a wide variety of civil and military aerospace machining tasks;

- The distance between OEM design and supplier manufacturing sites was some 200 miles by road;
- The nature of the product required complex CAD-designed mechanical machined parts to enable the highly-stressed system to achieve the required performance with minimum mass and volume;
- Because of the nature of the defence contract, the customer saw time-to-market as important, in that penalties were related to program lateness. Until recent 'smart' initiatives, there had been little incentive to improve time to market;
- The parts were required in relatively low volume and individual component cost was low; however, design risk and potential project impact were high.

The context was that of the Senior Designer offering the supplier's Production Engineers an opportunity to comment on the manufacturability of his design at an early stage in its development, when changes could be incorporated at minimal cost. Both parties knew that their questions, comments and observations would be critically discussed and analysed at the team meetings. They also knew that what they were doing had full management backing from both firms, and that there were no contractual or IPR barriers to prevent the full and free exchange of information.

For the purposes of analysis this dialogue between Design and Manufacturing was required to be recorded by both parties, including its nature, date and duration. The logbooks maintained were also used to record the man hours spent by Design in preparing material to be passed to the supplier, and the man hours spent by Manufacturing in assessing the material, noting problems and considering suggestions for improvement.

The team members had been working together over a period of several months during the preparation for the pilot phase of the project. The teamworking culture alignment was developed to promote interaction for the benefit of the project without regard to the affiliation of the originator. Encouragement was given for any relevant matter to be raised.

B.4.3 Monthly review meetings

The project team for SESAME was run as an Integrated Development Team (IDT), with a planned schedule of monthly meetings to review progress and discuss the technical producibility issues. The venue was rotated between the customer, supplier and university sites to provide an opportunity for team members to visit each other's workplaces. This also served to avoid any suggestion that any one party bore a greater responsibility for running the proceedings than the others. Social events were held to encourage people to get to know each other, typically in the form of a team dinner the evening before the day of the meeting.

Membership consisted of:

- The senior designer (who was solely responsible for the design of the SESAME parts);
- The IT group leader (responsible for the customer's process development, configuration management and standards);

- The procurement engineer and quality manager (responsible in their functions for the work placed with this supplier);
- Two production engineers (responsible for the shopfloor planning and manufacture for their machining work for this customer);
- The supplier's engineering development manager (responsible for process development);
- The university researchers (acting as facilitators, and responsible for recording the meeting minutes).

Each meeting consist of three parts:

- A formal (IDT) procedure to identify issues and to monitor their resolution;
- Detailed discussion on technical issues;
- Results-monitoring activities of the research team.

B.4.4 Producibility issues discussed (units of analysis)

Three formal iterations of the PI model were made over a period of six months. This timescale reflected a common working pattern for this size of project, where neither the Designers nor the Production Engineers were dedicated only to SESAME. A total of 13 technical issues were raised during the Producibility Interactions. These are summarised in Table B.1, together with the team's assessment of their importance, method of communication and impact.

Table B.1 SESAME producibility interactions

PART DESCRIPTION: Stainless steel (machined from stock)		Importance (tick one only)			Method of Communication (tick one only)			Impact of Issue			
Producibility issues		Critical to Design/Manufacture	Easements	Redundant Design	Personal Contact	Model Viewer	Drawing Only	Stage at which problem was or would have been picked up	Major or minor change		Full Mod or Drg Amdt?
									Design	Supplier	
S1	Mismatch undercut and rear face		✓			✓		First article	m	M	M
S2	Operating lengths - fit diameters requested		✓			✓		Never, unless tolerances not achievable	m	m	M

PART DESCRIPTION: Stainless steel (machined from stock)		Importance (tick one only)			Method of Communication (tick one only)			Impact of Issue			
Producibility issues		Critical to Design/Manufacture	Easements	Redundant Design	Personal Contact	Model Viewer	Drawing Only	Stage at which problem was or would have been picked up	Major or minor change: Design	Major or minor change: Supplier	Full Mod or Drg Amdt?
S3	Tooling hole needed		✓			✓		Manu Planning	M	m	M
S4	Supplier happy to accept CAD modelling method producing mirrored features, whereas Design had assumed generating them by rotation would help manufacturing			✓		✓		Never	m	m	-
S5	Change rectangular slot with small radius to full radius end		✓			✓		Manu planning	M	m	M
S6	Request for slot width to be increased due to concern about cutter head distance to wall; feature could not be changed, but wall height could be made smaller to facilitate cutter		✓			✓		Tape proving	M	M	M
S7	Alignment required for piston hole	✓				✓		N/A: would be shown on drawing	No change		-
S8	Tooling hole size and position discussed		✓		✓			Continuation of Issue 3	No change		-
S9	Add 8 off spot faces to M4 holes		✓			✓		Manu planning	M	m	M
S10	Engraving - can it be done by hand?		✓					Manu Planning	m	m	A
S11	What method of part marking? Omitted from original. Position important	✓						QA check of drgs	m	m	A
S12	Request to remove tight position tolerance on tooling hole (see producibility issues 3 and 8)		✓					Continuation of Issues 3 & 8	m	-	-
S13	Considered replacing 8 small slots with a proposed new slot design	✓				✓		Not technically allowed	M	-	-

Notes on the issues shown in Table B.1:

S1. The original geometry might have caused the inspector to query a witness line on the back face. Here, with the supplier in the loop (SIL), it was an easement, but under make-to-print (BTP) it could have been critical, especially if the first article was satisfactory and the problem only appeared later in production.

S2. Under BTP, Manufacturing would have attempted to achieve close tolerance on 2 diameters, increasing the cost of the part, raising a query only if they failed. A supplier used to working on missiles does not usually question high precision. The issue raised the designer's awareness of the need to specify more fully.

S3. This tooling-hole requirement could extend the timescale by months on a multinational project. Manufacture might have proceeded under concession, or at risk until a modification was approved.

S4. A radius to allow the tool to enter was possible either way. Rotation of the model to generate the four instances of the feature had involved more work for Design than using the mirroring facility of the CAD software.

S5. This avoided a tool change. Under BTP a proposal for change would probably not have been made unless as part of a cost-reduction exercise. The cost of a formal modification was likely to exceed the saving for the small batch required.

S6. Either a long-shank tool would have been used, or there was a risk of conflict.

S7. This showed the limitations of viewing a model: drawings would have shown relevant tolerances. The issue was raised because the model showed a piston hole on each side, and the query concerned whether the general tolerances could be applied separately to each hole, or whether it was important for the bores to be aligned with each other.

S8. Under BTP, this discussion would have taken place during the modification procedure.

S9. Alternative methods of achieving the result would have involved extra work. As for Issue 5, under BTP such a proposal for change would probably not have been made unless part of cost-reduction exercise.

S10. A note would have been added to the drawing: "May be done by hand". Such an amendment could be done by memorandum.

S11. The method of part marking could have been one of many specified in the standard quoted, and needed clarification.

S12. Without this change, inspection might have rejected a part as out of tolerance, when the exact tooling hole position had no effect on the correct part function.

S13. This initiative was possible only after the supplier had been shown a CAD model of the assembly at the previous working group meeting, and it had been made clear that the supplier could be 'radical'. It was proposed due to the manufacturing difficulty of the slots, and would have reduced costs if feasible. The proposal was reviewed by Design, who on revisiting the model found other problems with mating faces. While the supplier suggestion could not be accepted due to fit and functional requirements, the question initiated design development on the part of the Designer.

Points 10-12 were based on the Key Features Drawing (KFD), which was passed to the supplier with the second iteration of the model.

Importance

The issues were placed into one of three categories, according to their importance:

- 'Critical to Design or Manufacture' were issues raised to resolve problems that would have required either clarification or an engineering change before manufacture could proceed;
- 'Easements' were where it would have been possible to make the part, but a suggestion was made to ease manufacture;
- 'Redundant Design' covers the case where the designer had adopted a more time-consuming technique to generate the part design, because it was mistakenly thought that the part would be easier to make.

Method of communication

The principal method of communication that stimulated the raising or resolution of an issue was placed in one of three categories:

- Personal contact, including face-to-face and telephone discussion;
- Model viewer.
- Drawing only

Full drawings would not normally be produced until detail design was complete, but sketches or drawings of key features that could not be shown on the 3D model were produced for the second iteration of the model. Most points were raised as a result of the supplier seeing the 3D model on a viewer, but some only became apparent when shown on a key features drawing (KFD).

Impact of issue

The industrial collaborators determined the impact of each issue by assessing four aspects of what would have happened if there had been no Producibility Interaction SIL process. These are shown in Table 3.2 as follows:

- The stage at which the matter would have been picked up;
- Whether it would have required a major or a minor change by Design;
- Whether it would have required a major or a minor change by the Supplier;
- Whether the change would have needed a full modification, or could have been satisfied by a drawing amendment.

B.4.5 SESAME lessons

The principal lessons learned from setting up a concurrent engineering project of this nature in the extended enterprise were seen as:

B.4.5.1 Choice of project parts

No Project Manager will readily offer to involve a project with a new way of working, at a time when the budget for design has already been allocated, and project milestones have been set that include release of drawings. People needed persuading that the potential benefits outweigh the likely additional time and effort necessary to involve suppliers with Design.

AEROEXTN found that including the setting up of an integrated development team with a management plan and timescale for the pilot project was an advantage. It helped to show Project Management that there was not an open-ended invitation to extend the design phase against the vague hope that some time might be saved in production.

The actual choice of parts depended on the nature of the product and the characteristics of the supplier. The AEROEXTN team developed a decision support tool to facilitate the assessment of the factors relevant to determining whether and in what way suppliers should have early involvement with Design. The prime industrial collaborator's Procurement adopted the AEROEXTN module for characterising suitability for early supplier involvement in their Joint Improvement Management System (JIMS). Details of the decision support tool have not been included in this thesis, but were reported in a conference paper (Fan, Hernando et al. 1999).

B.4.5.2 Contracts and IPR

The supplier is naturally concerned at the possibility that his Production Engineering effort will be wasted if the customer does not proceed with the project. There may also be concern at the possibility that the customer may reap the benefit of his expertise and place the order elsewhere. These matters were addressed in the AEROEXTN Project and reported in a conference paper (Philpott, Hamblin et al. 1999).

B.4.5.3 Producibility Agenda

The team agreed on the importance of the PI Table as an agenda to ensure that questions were asked to cover all relevant matters, especially 'grey areas' where previous work had not met the customer's expectations. It had been helpful to learn of examples of earlier queries, or where the supplier's interpretation had not been what Design intended or Inspection would pass.

B.4.5.4 Industrial change

Industry frequently makes changes in its organisation for reasons of strategy (e.g. company amalgamations, factory moves, product rationalisation and outsourcing). Personnel involved in a project may be affected directly by such changes, or they may move in the normal course of career development, promotion or retirement. Such change is to be anticipated during the life of the project, and it is important that management should recognise the need to avoid losing the potential benefits of experience in ESI working. In the AEROEXTN case the involvement of the customer's Configuration Management and Procurement meant that they developed procedures which could be applied as standard practice to other projects, and where appropriate could be incorporated into new procedures which were being developed because of the industrial change. Traceability was an important aspect both for keeping track of what had occurred on the current project, including logging reasons for change against a particular stage or model, and for enabling a valid comparison to be made with previous projects.

B.4.5.5 Training and Publicity

An important element of the project was to ensure that the customer and supplier understood each other's business and terminology, and knew what was expected of them for effective ESI working. In the case of AEROEXTN, the team benefited from some of the supplier members having previously worked for the customer, before the manufacturing was outsourced. The team recommended that:

- Training support should cover the principles of ESI working, perhaps in an upgrade package for designers and project managers;
- Examples of the successes of ESI projects should be given maximum publicity;
- The problems and unsuccessful experiences should also be taught, together with an appraisal of the reasons and advice on how to overcome or avoid them in the future.

Appendix C Communication of Producibility with Design (the PI Table)

Table C.1 (See Chapter 3 Sections 3.4 and 3.6)

SERIAL	SUBJECT		GENERATED BY			ISSUES S = SESAME A = Al T = Ti C = Composites	METHOD OF COMM'N				REMARKS
			DES	MFG	OTHER		Personal contact	Model viewer	Drawing only	Full CAD only	
1	Concept/ problem at hand		✓	✓	✓						All team members are encouraged to comment on concerns, and raise any matter as soon as it occurs
2	Change since last review		✓	✓							Observations must refer to identifiable draft or release
3	Programme plan: cost/timescale/ no req'd/ milestones				Project Planners through Procurement						Progress on detailed plans should be shared where possible. Consider third party lead times
4	Risk Assessment-Design		✓								Opportunity to discuss design intent of features, materials, etc. that are new or may have caused difficulties in the past
5	Risk Assessment-Production			✓		A3					Opportunity to discuss processes, features, materials, etc. that are new or may have caused difficulties in the past
6	Initial CAD model	Status & date	✓					✓			Site A has CADDS 5 workstations. Site B has CADDS 5 in tooling area but not on assembly line
7		Physical Interface Definition	✓			T7		--			Geometry set at A scheme on CAD --- space allocation model for sizing. (Interface Definition not sent to supplier)
8		Material properties	✓	✓		C 1, 3, 4, 7, 8, 11, 13		✓ Mark up			Ensure process information available for new materials, and request trials if necessary. Check best use of stock sizes

SERIAL	SUBJECT		GENERATED BY			ISSUES S = SESAME A = Al T = Ti C = Composites	METHOD OF COMM'N				REMARKS
			DES	MFG	OTHER		Personal contact	Model viewer	Drawing only	Full CAD only	
9	Initial CAD model	Tolerances-key	✓			A4, 5 T5, 6		✓			Opportunity to discuss design intent for tolerancing
10		Tolerances-manufacturing		✓		S 2, 12 A1, 4, 5		✓			Dialogue to discuss difficult areas, including surface finish
11		Datum/ clamping	✓	✓		S 7, 8 C 8 T 5		✓			Non-physical datums may cause difficulties. Clamping may affect billet size – aim to minimise material requirements. Manufacturing may request tooling holes
12		NC programming ease		✓		S 4 A1 T 1, 2, 3					Opportunity to request adjustment to features for ease and speed of work
13		Manufacturing limits: Capability (processes)		✓		A1 T 4		✓			Capability captured for Design. (Note: Site capability brochure may not include capability for work on task-specific machines.)
14		Manufacturing limits: Capacity (size)		✓				✓			Consider also any special requirements for handling and transportation
15		Manufacturing limits: Capacity (throughput)		✓							Capacity study and capabilities. Time element of capacity may be affected by other work. Offloading to other machines or sub-contractor may require re-assessment of producibility
16		Special processes	✓			S 10 C 7, 10		✓ mark up			Early discussion of processes, especially if third party involved
17		Standards acceptability		✓		A5, 11 C 6, 10					Early discussion, especially if new or revised standards required

SERIAL	SUBJECT	GENERATED BY			ISSUES S = SESAME A = Al T = Ti C = Composites	METHOD OF COMM'N				REMARKS
		DES	MFG	OTHER		Personal contact	Model viewer	Drawing only	Full CAD only	
18	Key Features-Design 2-D drawings-req't for format & views	✓								Drawings required if not shown as mark-up on model
19	Key Features-Production		✓		S 11 T 5, 6		✓ mark up			Drawings required if not shown as mark-up on model
20	Model designer-Designer	✓								If produced, make available for Manufacturing to view
21	Test piece req't	✓	✓							Requirements in design handbook, or test programme for new processes. Usually required for composites
22	Process Plan		✓		S 1 A1					Generated by Manufacturing Engineering – includes flow. Also requires 23 and 24
23	Jigs & fixtures		✓		S 3, 9 C 2, 5,12				✓	Jig & Tool Design would match CAD component – discuss with Manufacturing as necessary
24	No of separate set-ups and machining activities, machine run time and specialist cutting tools		✓		S 4, 5, 6, 9, 13 A1 C 9 T 1, 2, 3					Discussion with Design may allow reduction in the number of different tools required

SERIAL	SUBJECT	GENERATED BY			ISSUES S = SESAME A = Al T = Ti C = Composites	METHOD OF COMM'N				REMARKS
		DES	**MFG**	**OTHER**		**Personal contact**	**Model viewer**	**Drawing only**	**Full CAD only**	
25	Integrated Development Team	✓								Would be set up for all high value/complex parts. Continuous Product Development (CPD) team reviews existing products
26	Inspection Requirements			Quality	S 12 C 10		Not accurate enough for inspection	Drawing data set	✓	Requirements agreed with supplier: Quality is part of CPD
27	Quality: Requirements for Manuf to Release			Supplier QA	S 1 A 1, 3					Company policy is for inspection at manufacturer, to Product Spec
28	Quality: Requirements for Assembly to Accept			Prime QA/ Procurement						Product Assurance Controller checks paperwork
29	Non-conforming parts			QA	T 5, 6, 7					Important to capture problems from Manufacturing and Assembly and feed back to Design

Notes on PI Table

1. This table is the principal tool of the PI Model that was developed during the AEROEXTN Project to facilitate communication. It serves to provide a comprehensive list of subjects for discussion between Design and Manufacturing, with Quality, Configuration Management and Procurement attending as necessary. Other specialists may be co-opted as required.

2. The intention is to stimulate discussion and ensure that each subject is properly explored, with nothing relevant being missed out.

3. The subjects are arranged in the approximate order in which a project is likely to progress. The nature of new product development is

iterative, and further points on any subject can be raised in any order, as more information becomes available or queries occurr to team members.

4. A low-cost viewer enables 3D part geometry to be downloaded from CAD systems, including Pro/Engineer, CATIA and CADDS 5, and displayed on a PC. Depending on the viewer software, the model can be rotated, zoomed, sectioned, annotated, and red-line marked up. Feature dimensions can be interrogated. Assemblies can also be viewed. E-mail or floppy disk can be used to send files, and a self-opening viewer included so that the recipient does not need a copy of the software or a licence in order to view the model. The viewer can be used by anyone with a little practice, and formal training is not needed. Such a viewer could be used to show an initial CAD model to a manufacturing department or a supplier, to enable them to view part features and assemblies, without the need for a full CAD workstation and the associated data link and operator training. This could be particularly useful as an aid to communication and discussion of producibility before the detail design was complete and before detailed 2D drawings were available. Design could answer queries and respond to the concerns of Manufacturing by making changes while they can be done at little cost before design freeze. The viewer can also be used to help Manufacturing understand the detailed features and plan their tooling and processes accordingly, rather than discover problems later and suffer the resulting delays and costs. Where facilities exist for Manufacturing to view full CAD models, there may be no need for a low-cost viewer – but such a viewer could be very helpful for showing sub-contractors what is intended.

Appendix D Civil Aerospace Studies

This appendix describes in detail the industrial studies involving both in-house and outsourced manufacture of parts for the civil aerospace industry summarised in Chapter 3, Section 3.7. Two major manufacturers allowed the author to collect data by talking directly to the people involved in the design-to-manufacture chain. In both cases, Company A was the customer responsible for design. The first study was of a mature aluminium alloy part, where a batch was currently being machined in house. The second study was of one set of titanium machined parts and one set of composite moulded parts, both being manufactured by Company B as a supplier to Company A.

The author used semi-structured interviews and group meetings to gather historical data, and conducted each study on-site over a period of five working days. The Producibility Interaction model developed for the AEROEXTN project was used as a tool to ensure that all relevant subjects were covered, and reviewed to confirm its relevance in the context of both internal and external supply.

D.1 In-house manufacture study

D.1.1 Study methodology – internal supply

The aim of the study was to capture information on in-house manufacturing problems in civil aerospace from the relevant functional specialists, by using a particular part that was currently in work as a vehicle to trigger discussions.

Although senior management had placed no specific constraint on the time that could be spent with the company, the author considered it prudent to limit the study to one working week, excluding the initial visit and any follow-up needed.

The first requirement was to ensure there was on-site support for the study. A working-level point of contact was established during the initial visit. He was made available to provide local knowledge and guidance, arrange meetings and interviews, and provide administrative support throughout the week of the study.

It was important to make sure that the people to be involved understood the nature of the research, the contribution that was expected of them, and that the study had been authorised by a senior executive the company. This was achieved by choosing a week when the appropriate people would be on site, arranging advance notification, and holding a short meeting to brief representatives of the functions and answer questions on procedures at the start of the study.

The sequence of interviews and meetings was given careful consideration. The author decided that it was appropriate to start immediately after the initial briefing with Manufacturing and Quality, combined with a visit to the in-house shopfloor, on Day 1. The points raised would then be discussed with Design on Day 2, followed by a visit to the off-site assembly shopfloor on Daily 3. Procurement/Purchasing would be fitted in when available. The morning of the Day 4 would be used to consolidate notes and prepare a presentation. The afternoon of Day 4 was reserved for a review meeting to discuss issues raised with representatives of the functions together as a team, to ensure that the results of the study represented a balanced consensus. The morning of Day 5 would be used to pursue any loose ends before leaving the site.

A proforma was used to facilitate the gathering of data and the preparation of reports. This was designed so that Manufacturing could raise each problem, or set of similar problems, and then comments could be added in turn by each of the relevant functions. The completed proformas would then provide a basis for the review meeting, and the Producibility Interaction table could act as a tool to stimulate discussion and ensure that no subject was omitted.

The author agreed to produce the minutes of the review meeting and circulate them to the company as a report of the study.

D.1.2 Nature of in-house part

The structural part chosen for the in-house study is referred to as Part A in this thesis. This was an existing part that had been produced by a series of external suppliers for a number of years. Following the business failure of the current supplier, a small number of sets was being produced by the in-house manufacturing facility, to keep the assembly line going until the new supplier could be brought online.

Part A weighed 30 kilograms, after being milled on a high-speed 5-axis machine in three stages from a solid aluminium alloy billet of of 800 kilograms.

This part was selected because it had been a particular problem for Manufacturing, with a high number of queries, change requests and concessions.

D.1.3 Study of in-house part

Manufacturing had experienced a total of 36 arisings on Part A, which they summarised on five report proformas that were then copied to the other functions and discussed with them.

Because Design had a heavy workload on new projects, they could not spare more than one engineer to attend the review meeting for the whole afternoon on Day 4. They did, however, agree to discuss the proformas and DFM in the Design Office. The author was privileged to have a two-hour meeting with the Head of Manufacturing Design, the Design Task Leader, the Design Team Interface Manufacturing Engineer and the CAD/CAM/ICAD Manufacturing Engineer. Discussion covered not only the design of Part A, but also the procedures developed for later designs. The Design Team Interface Manufacturing Engineer subsequently attended the review meeting on Day 4.

Manufacturing Engineering had been set up some years previously to provide an interface between Design and Suppliers, because direct contact previously had been found to lead to an uncontrolled increase in costs. While this provided a normal means of liaison, it did not preclude designers visiting supplier facilities, especially when new manufacturing processes were involved. Manufacturing Engineering had recently put considerable effort into advising an overseas supplier on how to make best use of their new high-speed machinery to fulfil a large contract that was awarded as part of a workshare agreement. Such 'Producibility Interaction' was in marked contrast to the AEROEXTN experience, where the production engineering expertise had been with the supplier.

Procurement were not available to attend the review meeting, but provided a very valuable briefing on the firm's procedures, including: bid packs containing product specifications, delivery schedule requirements, drawings and CAD data; tendering; capacity and capability analysis; 'first article' inspection, concessions and non-conformance investigations; configuration management, and processing of works query notes from suppliers.

Procurement recognised that in the past problems had arisen following a change of supplier. For example, where the previous supplier had made a part for years, had found that the tool made to the tool drawing was wrong, and had modified the tool without getting the tool drawing changed. When the new supplier made the part to the drawings, it did not fit the assembly. It was noted particularly that on-site Manufacturing, as an internal supplier, did not get the opportunity afforded to external suppliers to negotiate on delivery, cost and tooling, and to discuss any technical input. They were simply tasked with producing the parts to drawing. Manufacturing pointed out that a number of work packages were being brought back in-house, as they moved from old to new technology, and that they would normally look at the process of the current supplier before taking over. In the case of Part A, this had not been possible when the external supplier failed.

The visit to the assembly line shopfloor at Site B provided an opportunity to observe Part A being fitted into the aircraft structure, and the effect of out-of-tolerance parts. The Engineering Group Leader stated that the part number did not change on change of supplier. Assembly would therefore not be involved, except to be told that a trial part was coming, and any opportunity to change the manufacture of Part A would have been very low-key – perhaps someone would have asked "Any problems with Part A?" There was, however, a paperwork penalty on change of supplier because configuration management required all structural parts to be traceable. Also, because Site B had authority to vary the 'condition of supply' of a part, e.g. fastener holes might be specified as pilot-drilled only, there could be differences between parts from different suppliers to the same part number. Any concessions that had been made in the manufacture of a part would be received with the part documentation and checked by the Product Assurance Controller to ensure that they were compatible with the assembly.

D.1.4 Review of in-house part

The report on Part A presented details of the part and an estimate of the man-hours involved in addressing the manufacturing problems covered by the five report proformas. This was tabled at the review meeting on Day 4 (see Appendix D, Section D.1.1 – some details have been omitted to preserve commercial confidentiality).

The review meeting was attended by the Engineering Group Leaders from the Part A manufacturing cell and the Part A manufacturing project, the Design Team Interface Manufacturing Engineer, together with the Manufacturing Engineer and the new Quality Group Leader who had accompanied the author throughout the week.

Table D.1 summarises the issues, their importance, method of communication and impact in a similar manner to that used in Appendix B Section B.4.4 for AEROEXTN.

Table D.1 Manufacturing Issues for Aluminium Parts

PART DESCRIPTION: Part A Machined from Al billet		Importance (tick one only)			Method of Communication (tick one only)				Impact of Issue			
Issues		Critical to D/M	Easements	Redundant Design	Personal Contact	Model Viewer	Full CAD model only	Drawing only	Stage at which problem was/would have been picked up	Major or minor change		Full Mod or Drg Amdt?
										Design	Supplier	
A1	Use of 5-axis feature in place of angled cutters in 3-axis or 5-axis scanning		✓				✓		NC prog'g	m	m	A
A2	Geometry definition did not allow simple 5-axis machining		✓				✓		Prod'n plan'g	M	M	--
A3	Problems and errors with drawings, e.g. dimensions missing, notes and pictorial view not matching	✓						✓	Prod'n plan'g	m	m	A
A4	Web tolerancing expected to be too tight with current process	✓				✓			Prod'n plan'g	m	M	A
A5	Tooling hole tolerance too tight	✓				✓			Prod'n plan'g	m	M	A

Notes on the issues shown in Table D.1:

A1. Problems with the 5-axis features could be resolved with a recommendation given in the Design response. This action could be carried over on to other parts that had similar problems. Concern over the number of changes to drawings could be eased by inclusion of condition of supply as part of the drawing specification.

A2. The problem found could not have been identified from 2D drawings, so that a Design review with Manufacturing would not have picked up the issue. The CAD system used when these parts were designed produced only 2D drawings, and did not generate a 3D model of the part. Modelling would have picked up this issue on the basis that production of the solid model would have shown up the Manufacturing concerns.

A3. 2D drawings were prone to human error. The depth of the manufacturing review would not have picked up such errors. Insufficient communication may have taken place with previous suppliers, who had all used the same tapes and facilities, so masking the problem. Before there was a change of manufacturer, parts should be modelled. The outgoing quality and production process at the existing suppliers should be fully understood before any move.

A4. Revisions in general notes should resolve the issue. General notes from later designs would be included on all drawings where applicable. Time to achieve capability data would extend time frame.

A5. Revisions in the tolerancing standard would be required to overcome the issue fully. In the short term, a change could be made in line with later designs. The adoption of ISO standards could be reviewed to confirm acceptability, though concern was expressed by Design regarding the potential to increase tolerances. Manufacturing observed that their 5-axis machines were capable of positioning to an accuracy of 0.04 mm over a 4m x 2m bed, and the tolerance between tooling holes required by the standard could be achieved by adding a fourth stage of machining and allowing the part to cool before this. Adding this extra stage would require additional pallets and would slow the production rate.

The total cost of man-hours for Design, Manufacturing and Quality amounted to 246.4, over half of which involved raising and answering Works Query Notes. At an average cost per man-hour of, say, £40 this represents £10,000. Discussion with Manufacturing after the meeting calculated the cost of materials and labour for the 3 trial parts. Each billet was 800 kilograms at £5 per kg = £4000, and involved 13 hours' machining at, say, £100 per hour = £1300. Typically one would be scrapped, and the following two would be re-worked and concessed, costing an estimated £7000. While it was appreciated that the 5 axis machines were new and the process needed proving, any progress toward 'right first time' could generate considerable savings. This might be achieved by:

- Design liaison as part of project (this was not standard practice for in-house production of 'mature' parts);
- Fully-integrated CAD/CAM system;
- Solid models with design-for-manufacture consideration;
- Development capacity (allocated machine time);
- Confirmed manufacturing methodology to close the DFM loop;
- Cutter parameters must be proven - continuous improvement;
- Verification specialist to check methodology to brochure;
- Product assurance involvement at front-end to produce inspection plans and Key Acceptance Dimension (KAD) charts for operators' use;
- Production engineers and operators to run Tape Try Out (TTO).

Many of the problems had arisen because the task had been generated as an internal one for Manufacturing, as a switch from an external supplier that had failed. Some problems had been anticipated on the change to 5-axis machining, but others had not been eliminated by current procedures and had reached the shop floor to cause additional work. Concessions and Works Query Notes appeared to take an excessive time, except when there was a very urgent need for the parts, and tended to treat the symptoms rather than the cause. The very process of raising the reports and discussing the problems for Cranfield University DFM research during this week, culminating in the review meeting, had resolved a number of issues and had gone a long way toward having the causes recognised. Any DFM improvements would be carried forward to benefit future suppliers whenever there was a change of manufacturer.

D.1.5 Review of the PI Table – in-house manufacture

The PI table was reviewed in the context of internal supply. Each subject was addressed as follows:

- To confirm its relevance to the Part A problems.
- To confirm the relevance and completeness of the broad range of subjects, drawing on the experience of those present.
- To consider the method of communication, especially as to whether a low-cost viewer could be useful.
- To enter clarifying or amplifying remarks on aspects that would help to get the best results in the Company A application.
- Overall priorities.

Part A. The five reports on Part A had related directly to 9 of the 29 subjects. Only report No 2 was not related to the PI table, as it would have required the 2D drawings to have been converted to a 3D model of the part for the problem to have been identified before metal was cut. This had been estimated as requiring 250 hours of Design effort, and had not been done because of the 'mature' nature of the part. Design now recommended modelling of parts for all projects, following experience of the manufacture of parts for the latest design, where all parts had been modelled and design queries were virtually zero. If a major supplier insisted on receiving CAD models where only 2D drawings existed, this was normally agreed despite the current shortage of design resources.

PI Subjects. Each subject was considered in turn, and endorsed. The only change was to expand item 24 ('No. of separate set-ups and machining activities') to add 'machine run time and specialist cutting tools'. No new subjects were added.

Communication. It was agreed that representation of the initial CAD model by the use of a low-cost viewer on a PC, including mark-up of annotations where necessary, would allow communication of most relevant subjects. Exceptions were NC programming ease (item 12), Jigs and fixtures (item 23) and Inspection requirements (item 26), for which the full CAD models would be needed.

Remarks. Appendix B shows the revised PI table, complete with agreed remarks covering the Company application.

Overall priorities. The following subjects were nominated as covering the most important part of the PI process: 7, 9, 10,12, 13, 22, 23, and 24.

Validation. The PI model developed for the AEROEXTN project appeared to be a good fit to the Company application. It was agreed that it had the potential to reduce the problems reaching the shop floor, but only if it were properly recognised by incorporation into standard procedures and senior management allocated the resources required to allow the necessary communication to take place.

Cost effectiveness. The effort expended in carrying out the PI process, especially if integrated with existing procedures, was far less than the full cost of solving problems, which included not only man-hours but also increased work in progress and delays. Furthermore, the PI process was aimed at tackling the root cause, so that a change of supplier/manufacturer or future developments based on the current design would not result in repeating the same problems. It was appreciated that some subjects were already addressed in the new Design procedures.

D.1.6 Further Observations:

The author gave the review meeting a CD-ROM demonstration of a low-cost viewer (of the kind used for the SESAME pilot in AEROEXTN). Such software enabled 3D part geometry to be downloaded from CAD systems, including CATIA and CADDS 5, and displayed on a PC. The model could be rotated, zoomed, sectioned, annotated, and red-line marked up. Feature dimensions could be interrogated. Assemblies could also be viewed. E-mail or floppy disk could be used to send files, and a self-opening viewer was provided so that the recipient did not need a copy of the software or a licence in order to view the model. The viewer could be used by anyone with a little practice, and formal training was not needed.

It was accepted that such a viewer could be used to show an initial CAD model to a manufacturing department or a supplier, to enable them to view part features and assemblies, without the need for a full CAD workstation and the associated data link and operator training. This could be particularly useful as an aid to communication and discussion of producibility before the detail design was complete and before detailed 2D drawings were available. Design could answer queries and to respond to the concerns of Manufacturing by making changes while they could be done at little cost before design freeze. The viewer could also be used to help Manufacturing understand the detailed features and plan their tooling and processes accordingly, rather than discover problems later and suffer the resulting delays and costs.

Manufacturing considered that the low-cost viewer could be useful as a development tool, but was concerned over the communication of design intent.

Design stated that CADDS 5 models were given out at A and B schemes. ‘A’ schemes had limited detail, sufficient for example to define approximate billet sizes. The ‘B’ scheme was more detailed, to allow tooling. The adoption of the knowledge-based ICAD system for future modelling should pick up problems, but its impact on designs had yet to be confirmed. It was understood that where ICAD was used to develop a generic part, the detailed model for each particular part would not be generated until the design was complete. Subsequent discussion confirmed this, but it was explained that the particular instance of an ICAD-generated part could be produced at any stage of its development – for example to enable it to be passed to Manufacturing for comment.

Manufacturing observed that all items in a standard tool pack, of say 30 tools, might be needed to do a job when enhanced communication with Design might have allowed this to be reduced to, say, 10 tools.

D.2 External supply

D.2.1 Study methodology – external supply

The approach to the study where the supplier was external was identical to that for internal supply in Section D.1. The only differences in the execution were a consequence of the contractual status and geographical separation between the customer and the supplier, here referred to as Company A and Company B.

The author took great care was taken to ensure that he did not breach confidentiality by passing information between the two firms without their express consent. In practice, no difficulties were encountered, because there was good co-operation between them, and they were very open in discussing design for manufacture problems with the author. Working level contacts, to arrange meetings and provide on-site support, were provided by Procurement in Company A and Manufacturing Projects in Company B.

The sequence of the study was the same: an initial visit to Company B to discuss the study and select suitable parts; Day 1 and Day 2 at Company B for a briefing meeting and capture of the manufacturing problems; Day 3 and Day 4 at Company A to discuss the problems with Design, Quality and Procurement; and Day 5 at Company B for the review meeting, with Company A represented. Unlike the in-house study, the dates on which people were available resulted in a time gap between the three site visits. This study therefore took longer than a working week to complete.

D.2.2 Nature of outsourced parts

Two sets of parts were selected for this study. Both were derivatives of earlier designs, but were new parts that had been fully modelled in 3D CAD. One was a set of titanium parts (Parts T) machined from forgings and the other a set of composite panels (Parts C).

Titanium is a hard metal that is difficult to cut and requires special tools. Because of its strength and relatively low density it is used for highly stressed components, such as engine attachment fittings. All material for Parts T was bought in as forgings, already stress relieved. The forgings had a long lead-time, and for some parts they contained extra material to allow for the future development of the aircraft without changing the supplier's tooling. Manufacturing involved: rough cut machining on 4-axis machines, ideally plus 3 mm to form; heat treatment for stress relief (because so much material was removed – but improved cutting tools in future may induce less stress); semi-finish machining to half mm; finish cut on both 4- and 5-axis machines; shot peening, zinc spraying and painting. Some parts had bushes fitted by Company B.

The composite parts were exterior panels with compound curves to provide the required aerodynamic profile. Manufacture involved the following processes: cutting to shape pieces of pre-impregnated carbon fibre, aramid fibre (kevlar) or glass-fibre cloth; placing the pieces accurately into a female mould with the preformed honeycomb inserts in the the correct sequence and with the correct orientation; placing a caul plate to consolidate the fibres in specified areas; vacuum bagging; curing under high temperature and pressure in an autoclave; de-bulking the vacuum bag and associated materials; trimming the panel edges and drilling the tooling and fastener holes with a high-precision ICY machine; coordinate checking and ultrasonic testing. A thin layer of aluminium foil that was required for electrical bonding and lightning protection could either be placed and cured with the main layup, or applied and cured separately to avoid outgassing problems.

D.2.3 Study of outsourced parts

Company B had experienced a total of 7 Arisings on Parts T, and 13 Arisings on Parts C. These were discussed on Day 1 and Day 2 and subsequently summarised on proformas for discussion with the functional specialists at Company A.

The author's discussions with Company B on Parts T were principally with the Manufacturing Project Manager for the Company A work, the Section Leader in NC Programming who had been heavily involved in meetings to discuss Producibility with Company A over a 12-month period some two years previously. Similarly, Parts C were discussed with the contract engineer from the Composite Engineering Department who had been in regular communication with Company A during development of these parts.

The following points were made in respect of the work on hard metal parts (Parts T):

- Problems had been encountered in data conversion from CADDS 5 at Company A to CATIA at Company B. IGES wireframe (not volume) was tried, but they found that Theorem worked satisfactorily. The NC programming was done from CATIA. Wireframe could be used for three-axis work, but a solid model was needed for 5-axis surfaces. Model sizes of 3 MB became 12 MB in CATIA, but 8 MB in CATIA via Theorem. Trials had been undertaken to prove the system, verifying back to the CADDS 5 model. (Note: Company A paid the cost of conversion, but the main problem was lead time, some 5 to 6 weeks overall.)
- Company B Production had visited Company A when the design was virtually complete, and was invited to comment. They agreed to add a ruled surface (cheaper to machine), but insisted that the top face on the pintle must be produced 5-axis (this is the only 5-axis feature on the part – scanned features were requested, which would have allowed parts to be made on a 4-axis machine). The shot-peening requirement was currently under consideration at Company A, and may not be needed (this would save the days taken to move the parts to the shot bay, queue, peen and return). The original corner radiuses were too small for deep pockets (a 170 long cutter would have been needed – the aim was to keep within 3 to 4 D to avoid slowing feed and speed); this change had been accepted. To a avoid using a shaped cutter, a 5-axis landing was agreed.
- Company B was involved in weekly (internal) and monthly (with Company A) meetings to discuss parts over a 12-month period. Points would be raised at meetings with no set agenda. These meetings started about halfway through model design and had continued until the first set of parts was completed. Operators were sometimes included: they were responsible for scheduling their machines – if a suggestion saved machine time, they could put more work through and the cell would be more successful. Cell engineers had CATIA,

which Operators could look at to view models. Quality Engineering and an inspector from the shopfloor were sometimes included in the Company A meetings to discuss the location of inspection points.

- NC programming should be considered at an early stage, as the sequence in which the CAD model was built up could make a big difference to the ease of NC programming. (Note: the ease of NC programming must be from the full CAD model, but an early model was useful to see the way it was constructed). In all cases, Company B would produce a CATIA model. Where earlier parts had been designed on ANVIL 2D, these would now be modelled in CATIA as a 'manufacturing' model, which could not be used for anything else. For a typical part, the effort to generate a CATIA model was about 2 weeks, and the NC programme would be generated in 3 to 4 weeks. The manufacturing model would not need corner radiuses, because the cutter size would be known – but a similar level of work was needed to produce a full Design model. If a part had previously been made elsewhere, Company B would re-post-process the previous NC programme for their machines.
- Contact outside the meetings was by e-mail, fax (including sketches) and telephone. Company B Production regarded communication as excellent, allowing direct discussions and enabling problems to be solved as quickly as could be expected. The current Company A Purchasing Engineer, who had briefed the author about the Company B work during the Part A study, had himself become involved part way through the development of Parts T.
- Company B would design their own tooling, in CATIA for new work, using the same design modelling as for the part itself. The inspection programme would also be written from the CATIA model.
- Company B had been allowed to specify the requirements for the forging design, enabling them to keep the same hole positions for all brackets, use the same fixtures and the same storage. This saved set-ups, as three operations could be carried out on components on the same set-up. The preliminary forging drawings for the part had been models by Company A in CADDS 5, converted via Theorem and used for VERICUT.
- Company B Production's comment on concurrent engineering: "It is important for the right people to meet, with knowledge of detail to the right level."

The contract engineer from the Composite Engineering Department was part of the IPT for Company B internal supply supporting the manufacturing department for carbon fibre parts. He made the following points in respect of the work on Parts C:

- Company A had sent 2D drawings as pre-issue copies for a set of Parts C panels. The designer was good on CATIA, but he was not a 'carbon' designer, and Company A had a lot to learn about carbon-fibre manufacturing.
- Two examples of the lack of appreciation of composite manufacturing involved specifying alternative plies of two types of material, and varying the thicknesses of the 'landing' areas in between the honeycomb cores. Changing to 12 plies of woven material, instead of six of woven and six of unidirectional, allowed both a saving in the cutting operation and an easier lay up. Redesigning the landing

areas to be the same thickness greatly simplified the caul plate that was placed over them in the mould to help consolidate the plies. These made manufacturing easier, and also inspection (because the tolerance on all parts of the landing was the same).

- Honeycomb cores were much easier to model in CATIA. The CATIA model would be sent to Hexcel, who produced 3D shaped cores with a net edge that saved hours of production time.
- 'Fiber-sim' software was used to access CATIA data and develop ply-by-ply lay-up details, including tooling holes in plies. The use of CATIA was a big advantage compared with CADDS 5 for working with Fiber-sim.
- Cured parts were trimmed on an ICY machine on which they had a capacity problem (note: a subsequent tour of the facility revealed that this 5-year-old machine was regularly breaking down). The first five articles were required by Company A to be inspected on a CMM, which were also had capacity problems. A 2D laser inspection checking system was used. All completed parts were subject to ultrasonic testing; the rig in the workshop was capable of testing large-area panels.
- Honeycomb and shear laminate test pieces would be included in the cure lay up and co-cured with a set of panels. They would subsequently be cut up and tested.
- Composite moulds were 5-axis machined from the CATIA model. Nylon locating pins were placed in moulds to locate the lay ups, the caul plate and the honeycomb template. After cure, the nylon pins would be drilled out to provide tooling holes for subsequent processes – these holes might be situated in lugs outside the area of the finished part. When a design change reduced the length of a panel by 100mm, the tooling change was minimised by keeping the original edges and tooling holes.
- Company B worked very closely with Company A during the development of the part. Contact started with the preliminary issue 001 of drawings, on which they raised 21 points (of which 18 were accepted).
- The composite shop in Company B never previously had the 'first article inspection' proved. Company A Supplier Instructions now required a first-off verification. Once this had been done, Company A accepted the process map, including kitting and autoclave cure details, as an 'approved manufacturing route'.
- When a part was rushed, Company B would work to 'model as master'. There would be a buy-off process on the ICY machine for hole centres and edge of part.
- Composite panel size was limited by the ICY machining facility. The machining area was approximately 4 m by 2 m. In the case of Parts C, a set of 4 panels could be loaded simultaneously onto a frame. Frames were loaded automatically into the temperature-controlled chamber while the previous parts were being machined, allowing time for the temperature to stabilise before cutting.

The author took the opportunity at Company B to receive a presentation by the R & T Simulation Development Engineer on the automation of engineering processes:

- CATIA Generative Shape Modelling used associative multi-model links to generate a functional model of a component, which could then provide the component detail model and the downstream tooling. For example, a shape could be defined by its con tour and centre. E.g. the centre may be associated with the centre line of a pipe. If it subsequently became necessary to re-route the pipe, the centre could be moved (thus moving the contour) and the changes would then cascade to all associated models.
- Tooling design for parts modelled in CATIA could be generated very quickly using Prescient Technologies' 'StoneRule' software. A demonstration was given of the design of tooling to form a sheet metal part – this could be done in 5 to 10 minutes, instead of 11 hours.
- Dassault Systèmes 'DENEB' software was demonstrated. This suite included assembly simulation and machining simulation. The original CAD model could be read in for the simulation to show how the parts would fit, check for collisions/clashes, and enable Production to look at an animation of the assembly process. Virtual numerical control (VNC) could simulate machining, including collision checking and probe measurements for GD & T. Careful control of process factors was necessary.

A Quality Manager from Company B expressed the view that time was the problem on the parts for this aircraft project. It had been demanding, with no time to devote to correcting/reinforcing learning. Attention to detail had been the nitty-gritty of the problem (he compared this situation with the past, when the aircraft drawing office had employed 600 men attending to detail). He saw all the problems as being related to communication – the knowledge and understanding existed within the organisation. He recommended that suggestions schemes could be used more. He claimed that Company B had been involved too late on the parts for this aircraft programme. The models by then were quite mature, but needed significant change for manufacture (e.g. ruled surfaces, corner radiuses) – independent of who manufactured parts.

The author held a meeting on Day 3 with Company A in the Design Office. This was attended by the designer who had been responsible for some of Parts T, the designer responsible for Parts C, a quality manager and the Procurement Projects Manager responsible for both hard metal and composite parts with Company B. The Engineering Task Leader was unable to attend, because he was on paternity leave – but, as this event had been anticipated, the author had the benefit of a telephone discussion with him the week before.

Further discussions were held on an individual basis with Procurement, Quality and Design during the rest of Day 3 and on Day 4. In particular, the Composite designer took considerable trouble to explain his design approach, because he was about to leave the firm and would not be available for the review meeting or any subsequent queries.

D.2.3.1 Review of outsourced parts

Details of Parts T & Parts C were tabled at the review meeting at Company B on Day 5 (see Section D.2 – some details have been omitted to preserve commercial confidentiality). Unlike the study of Part A, separate proformas had not been raised for each type of problem; details were compiled directly in the form of Tables C.2 and C.3 below.

Company B was represented at the review meeting by the Manufacturing Project Manager for the Company A work, the Section Leader in NC Programming and the R & T Simulation Development Engineer, Manufacturing Processes.

Company A was represented by the Procurement Projects Leader responsible for Company B work and the Quality Group Leader who had accompanied the author throughout the week of the Part A study. Company A representation was limited by the geographic separation – Design did not normally travel to suppliers unless there was a specific part or process to view; they could not justify the time or the funding on this occasion.

Apologies were received from the contract engineer from the Composite Engineering Department.

Tables D.2 and D.3 summarise the issues, their importance, method of communication and impact in a similar manner to that used in Table B.1 for AEROEXTN and Table D.1 above.

D.2.3.2 General observations on context

Company A pointed out that the aircraft project had originally being planned with the expectation of minimum change. The programme therefore worked to short lead times, which put pressure on Design resources when more extensive changes were found to be necessary.

With new technology about, it was not clear how designers found time to learn the developments in their field. The composite designer had found it very difficult to get away for seminars and similar forums for updating expertise. Company A employed a significant number of contractors, and it was not usual for them to be sent on courses to update their skills.

When asked what was the current level of understanding of manufacturing processes, Company B stated that it was common to survey the skills of the team to identify capability. Company A said that normally the Design Group lead designer would advise – however, owing to shortage of staff, there had been no Design Leader for the composite panels.

Company A expressed the need to have a mechanism for embedding processes. Much was down to individual capability, but the benefit of such skills should be made available to all. There was a need to look at the risks to the business of not embracing changes, otherwise there was a danger of getting 'another structure the same' rather than a significant improvement for a major new project.

Company B observed that small-work-package CE teams worked very well, but large-scale pressures tended to reduce their effectiveness, as a large work package was not seen as a group of small packages.

Asked if there was a well-defined process with clear visibility, Company A stated that such a process existed for the current project, but not enough people had been on the floor to do the job. The teams for the new project were working on a work breakdown structure following the A-B-C scheme route, trying to get far more Manufacturing information into each team, including: Datums; key characteristics for assembly; DFM handbook for designers; capacity of manufacturing machines; and transportation. The 'reality check' included health and safety and a black list of part/problems.

Forgings were a long-lead-time item (8 to18 months). Lead times varied from component to component, reflecting the differences in material, shape, size and complexity. The lead times for all Pylon forgings (Titanium) were 10-12 months. Pintle forgings were in the region of 8-10 months After the above lead times un-approved forgings would be ready for machine tape try-outs, 'Forging approval' would run concurrent with machine trials; if the forgings were then approved, any successful tape try-out would be allowed to be flown. As soon as the Forging Supplier was known Company A invited all machining participants to suggest any additional Manufacturing requirements (e.g. tooling lugs, etc). In the current project, Company B had been 'ahead of the game' in evaluating manufacturing issues, but no one had been able to provide early answers. The actions possible from the A scheme had been limited – no tool designs or ordering. Company A stated that a Purchase Order could not be raised until drawings were released, but a new set of commercial rules allowed an Authority to Proceed (ATP). However, some companies refused to work with an ATP. The new project had a different approach with DBTs.

Well-defined rules could be used for design. Company B had been looking at building design rules into CAD applications. These may be parametric constraints. An application might generate error messages for minimum thickness, radius etc. KBE could be a very effective means of incorporating manufacturing rules at the design stage to prevent problems. Company A was using ICAD to generate wing geometry; the ribs were major reported successes. Company B used StoneRule as there were problems for ICAD to output CATIA geometry. KBE worked only when rules were well defined, but not all problems could be expressed in simple rules. Some rules would be general, and some related to early CAM tools: there was therefore a need to know why each rule had been formulated. It was suggested that a future way to embed process improvement was the integration of manufacturing rules in KBE, but it might be several years before this could be realised.

Full CAD models exchanged between Company A (CADDS 5) and Company B (CADDS 5 & CATIA) provided Manufacturing with ready access to geometric details. Following discussion it was agreed that a low-cost viewer would have been adequate to enable the issues to have been identified. This could be a more cost-viable option for smaller suppliers.

D.2.3.3 Communications and teamworking

Company A would not normally go to a supplier or potential supplier until the end of B-scheme design, other than for general matters. However, suppliers should be alerted to key characteristics, and it was pointed out that much early work had been done on new aspects of the current design, where made test pieces had been made and proposals submitted.

During the development period of the current parts, both companies had held regular in-house meetings. These had been organised under the IPT at Company A and the by the Manufacturing Project Manager at Company B. Inter-site meetings were initially held at

Company A on a monthly basis; later as the jobs got into Manufacturing, meetings were held at Company B to allow Company A people to see the processes.

Electronic communication between sites was on a daily basis by telephone, fax and file transfer. The Optegra system at Company A had been set up so that Company B could view relevant files on the server. It was suggested that virtual teams could have been formed, and the importance of the culture issue was emphasised in gaining acceptance of conflicting points of view.

To maintain the integrity of procedures, works query notes (WQNs) had been raised. Prior to the meeting, Company B had expressed concern that responses to non-priority WQNs routinely took 2 to 4 months, and had suggested that there should be a service level agreement to provide (say) a 30-day response. All faxes sent by Company A were registered copies, to ensure traceability. It was noted that Company B had not been registering their faxes. Models put on the server by Company A were registered via the Data Exchange Group.

Concern was expressed as to why it appeared that the problems of earlier aircraft projects were being repeated: there may be a requirement to cut corners, but there should be a systematic approach. There did not appear to be the fundamental tools for Design into Manufacturing, and there was no mechanism for escalation, effectively to weight concern as a business issue. Company A responded that mechanisms were in place, work had been concentrated on priorities for current project, and the efforts did produce the parts. However, the original planning for the project had been unrealistic in timescale and in the expectation that there would be no requirement for new jigs. The biggest impact on programmes would be achieved by improving upstream planning.

D.2.3.4 Costs

Information was not readily available to assess the detailed costs involved in people travelling and participating in meetings, and the costs saved as a result of doing so.

D.2.3.5 Producibility issues raised on hard metal parts

A total of 7 issues had been raised on the three types of hard metal parts referred to as Parts T (Pintle Fitting, Engine Pylon Bracket, and Retraction Jack). Table D.2 summarises these issues, their importance, method of communication and impact in a similar manner to that used in Section B.4.4 for AEROEXTN and for Part A in Section D.1.4.

Table D.2 Manufacturing Issues for Titanium Parts

PARTS T DESCRIPTION: Jack mounting Pylon Brackets Pintle Fittings Machined from Ti forgings		Importance (tick one only)			Method of Communication (tick one only)				Impact of Issue			
Issues		Critical to D/M	Easements	Redundant Design	Personal Contact	Model Viewer	Full CAD model only	Drawing only	Stage at which problem was/would have been picked up	Major or minor change		Full Mod or Drg Amdt?
										Design	Supplier	
T1	Ruled surface added (Pylon)		✓			✓			NC prog	m	M	M
T2	Change of corner radius on deep pockets (Pintle)		✓			✓			NC prog	m	M	M
T3	5-axis landings requested /added (Pintle)		✓			✓			NC prog	m	M	M
T4	Bush insert for grease nipple hole (Pintle)	✓				✓			Damage to hole	M	M	M
T5	2D drawing GD & T datum errors (Jack)	✓						✓	Inspection	m	M	A
T6	Models created to nominal dimn on ++ tols (Jack)	✓						✓	Inspection	m	M	M
T7	Pintle locking block radius in wrong position	✓				✓			Assembly	m	m	A

Notes on the issues shown in Table D.2:

T1. The original inside surface had been generated on the CAD model using a constant thickness from the outside double-curvature surface. Changing to a ruled surface allowed to the used of a standard rectangular cutter, instead of a shaped ball or barrel cutter, allowing much faster machining. Any NC programmer would have picked this up. Company A pointed out that the change of inside surface from a constant thickness to a ruled surface was agreed and incorporated very early on in the design phase, but compromised the design of the component to enable a manufacturing easement.

T2. The pockets were deeper than on the previous design, and the change allowed the cutter size to be kept to the maximum for faster cutting. This requirement could have been on a rule base for design. However, the designer had commented at the Company A meeting (on Day 3) that he had learned only from talking to a current Manufacturing practitioner that it was possible to use a cutter with more than the 3: 1 height-to-width ratio that his producibility engineer colleague had advised.

T3. The use of a 40 mm diameter rectangular cutter inside the acute angle of the pintle allowed faster cutting, but left a 'landing' wedge of material that increased the weight of the part. Design were prepared to accept this penalty.

T4. The addition of a grease nipple resulted from an in-service problem of grease not reaching all round the pintle fitting. The original proposal had called for this quite complex feature to be put directly into the titanium, with the possibility of damage leading to the whole part being scrapped. Much interaction had occurred between Manufacturing, Design and Testing before Company B's proposal using a bush had been adopted.

T5. Errors had occurred on the Pintle because the designers had changed, and GD & T were generated from the wrong datum. Tolerances were not seen from the 3D solid model.

T6. This was discovered on assembly, when a bearing was found to be slack instead of an interference fit. The tolerancing had not been given on the model, but came out later with a drawing. It was possible that the designer may have picked up wrong information on a proprietary bearing. It was noted that this aircraft project had for the first time used minimum-content 2D drawings, and the operators had needed more information.

T7. This was a design error in the locking block for the pintle. Normally, such an error would have shown on clash detection and been corrected before reaching Manufacturing, but the part was a late requirement and time pressure had contributed to the mistake not being found. It would have been possible to detect this using a low-cost viewer showing the assembly of this part.

D.2.3.6 Producibility issues raised on composite parts

A total of 13 issues had been raised on the four types of composite panels referred to as Parts C. Table D.3 summarises these issues, their importance, method of communication and impact in a similar manner to that used in Section B.4.4 for AEROEXTN, for Part A in Section D.1.4 and for Parts T in Section D.2.4.4.

Table D.3 Manufacturing Issues for Composite Parts

PARTS C DESCRIPTION: Composite Panels (4 Off Each Hand)		Importance (tick one only)			Method of Communication (tick one only)				Impact of Issue			
Issues		Critical to D/M	Easements	Redundant Design	Personal Contact	Model Viewer	Full CAD model only	Drawing only	Stage at which problem was/would have been picked up	Major or minor change		Full Mod or Drg Amdt?
										Design	Supplier	
C1	Alternate plies of woven and unidirectional carbon changed to all woven ABRI 0023		✓					✓	Production planning.	m	M	A
C2	Landing areas redesigned to be the same thickness throughout the panel	✓					✓		Tooling	M	M	M
C3	Honeycomb ribbon direction different from earlier panels.		✓					✓	Honeycomb manufacture	m	M	A
C4	Deletion of outer surface Tedlar film.		✓		✓				Production planning	m	m	A
C5	Use of technology from another supplier project for tooling for bonding and routing.	✓			✓				Design	M	M	M
C6	Use of Fiber-sim for ply development.	✓			✓				Design	M	M	M
C7	One shot foiling of panels.		✓					✓	Production planning.	m	m	A
C8	Addition of tooling holes for customer assembly jig pick-up.	✓					✓		Assembly build	M	M	M
C9	All plys to be one-piece plys (ref item 6)	✓			✓				Production planning	M	m	M
C10	Ply drop-offs designed incorrectly for aesthetics.		✓					✓	Production planning	m	m	A
C11	Incorrect specifications for formed honeycomb core.		✓					✓	Honeycomb manufacture	m	m	A
C12	Elimination of core filling.		✓		✓				Production planning	m	m	A
C13	Addition of Synskin for surface finish.		✓		✓				Paint prep.	m	m	A

Notes on the issues shown in Table D.3:

C1. This allowed all 12 pieces of cloth to be cut from one roll of fabric, instead of six from each of two types of cloth. Design had considered the differences in strength and weight of the panel to be acceptable.

C2. The original mid-80's design had been difficult to manage and expensive on tooling.

C3. Certain honeycomb cores would not form with the ribbon direction as specified – this had not been a problem for flat cores used elsewhere.

C4. This had been an unnecessary carry-over from the earlier design.

C5. A change was necessary to keep the tooling holes standard for the tooling route.

C6. The Design culture at Company A differed from the expectations of Manufacturing at Company B. Design regarded it as their responsibility to define the finished boundary of each ply, while Manufacturing were used to having the CATIA adjunct programme Fiber-sim develop the cutting schedule for each ply. Company A did not use Fiber-sim, but had agreed to arrange for a subcontractor to apply the programme.

C7. Company B was allowed flexibility as to whether they co-cured the aluminium foil backing-layer with the main panel lay up, or applied it in a separate lay up. This had materials as well as process implications, because out-gassing had been one of the problems with co-curing and a possible solution would have been to adopt a perforated or expanded foil rather than a solid foil. The cost of this might have been less than that of the second cure.

C8. This was an assembly requirement, not originally identified.

C9. Manufacture requested one-piece plies because these could more readily be laid up on the locating pegs than separate pieces that had to be located using templates. This was, however, less economical in the use of cloth.

C10. Acceptable to Design, but would not have passed Company B inspection.

C11. A correction to the specified material, which was readily apparent to Manufacturing.

C12. Possible as a result of the common thickness of landings introduced at Issue 2.

C13. This extra thin layer was to eliminate surface pinholes, and should result in a cost saving in finishing.

The composites designer had considered issues C1, 4, 7, 8, 11, 12 and 13 to be of general applicability, regardless of the supplier, while he saw issues C2, 3, 5, 6, 9 and 10 as being specific to the Company B site. He had also suggested that Design would have been prepared to address a 'wish list' of issues raised by suppliers before detailed design commenced.

D.2.3.7 Review of the PI Table – external supply

The PI table was reviewed in the context of external supply. Each subject was addressed as follows:

- To confirm its relevance to the Company A/ Company B DFM problems.
- To confirm the relevance and completeness of the broad range of subjects, drawing on the experience of those present.
- To consider the method of communication, especially as to whether a low-cost viewer could be useful.
- To enter clarifying or amplifying remarks on aspects that would help to get the best results in this application.

PI Subjects. Each subject was considered in turn, and endorsed. No new subjects were added.

Communication. It was agreed that representation of the initial CAD model by the use of a low-cost viewer on a PC, including mark-up of annotations where necessary, would allow communication of most relevant subjects. Exceptions were NC programming ease (item 12), Jigs and fixtures (item 23) and Inspection requirements (item 26), for which the full CAD models would be needed.

Remarks. Appendix C shows the revised PI table, with agreed remarks covering the Company A/Company B application.

Validation. The PI model developed for the AEROEXTN project appeared to be a good fit to the current application. It was agreed that it had the potential to reduce the problems reaching the shop floor, but only if it were properly recognised by incorporation into standard procedures and senior management allocated the resources required to allow the necessary communication to take place.

Cost effectiveness. The AEROEXTN project had shown that the effort expended in carrying out the PI process, especially if integrated with existing procedures, was far less than the full cost of solving problems, which included not only man-hours but also increased work in progress and delays. Furthermore, the PI process was aimed at tackling the root cause, so that a change of supplier/manufacturer or future developments based on the current design would not result in repeating the same problems. It was appreciated that some subjects were already addressed in the current project procedures, and it was expected that a more structured approach would yield further benefits.

D.3 Application of the Producibility Interaction Model to civil aerospace manufacture

The PI Table originally developed for the AEROEXTN project was accepted as being both relevant and complete by the industrial practitioners who participated in the civil aerospace studies. No new subjects were suggested or introduced, and the only changes made to the wording were to make it more general, rather than specific to AEROEXTN. Although the participants in the civil aerospace studies all had access to full CAD systems for viewing design models, they agreed that a low-cost viewer could have been used for most purposes. In particular, such a viewer could have helped to convey the design intent in discussions with suppliers who did not operate full CAD systems, although (after observing a brief demonstration) Manufacturing at Company A had reservations about its capabilities.

The most important aspect of the PI Table is its use as a tool to assist management to structure discussions between Design, Manufacturing and other relevant functions at an early stage in the development process. While cooperation between Company A and Company B appeared very good, it was clear that some aspects could have been started earlier. This may have been affected by strategic decisions on sourcing, which had not finalised on Company B before detailed design commenced.

The producibility discussions between the two companies that had taken place during the development of Parts T and Parts C were on an ad hoc basis and unstructured. In the case of the composite parts, Design stated that they would have been prepared to accept a 'wish list' from the supplier at an early stage. It may be significant that Company A at the time had no Design manual for composite parts, and that the only site-specific issues raised were related to the manufacturing processes of the composites supplier.

Appendix E Report Proformas

E.1 In-house manufacture

Summary Report for Part A

Part A	**Size** 115x3178x692	**Material** Al plate 7010

Weight 30kg from 800 kg billet	**Assembly** --	**Aircraft/project** --	**Quantity/production rate** 6 sets (12 off)

Classification: ☐new/prototype ☐derivative ☐improved version ■ **ch of manuf**

☐high volume ■ **small batch** ☐one-off

Designed by: Organisation: A	**Location:** Site A
Drawing/part number: --	**Date:** 1992
Manufactured by: Organisation: A	**Location:** Site A
Manufacture Release - Inspected by: A	**Location:** Site A
Acceptance for Assembly - Inspected by: Organisation A (paperwork only)	**Location:** Site B

Process (type -- primary/secondary, treatment; new or familiar to manufacturer):
Milling from rolled 7010 plate in three stages, on new 5-axis machines

Arisings (see following reports for nature, action and time to resolve, design effort, tooling changes, wasted materials, delay to production, cost & relation to PI Table):

Summary of Arisings and man-hours	Report No	Total Arisings	Design Man-hours	Manufacturing Man-hours	Total Man-hrs
Engineering Queries	2	1	2.6	3.5 + 4.8 = 8.3	10.9
	3	11	110	44	154
Engineering Changes	1	1	7.8	1.7	9.5
Scrap and Re-Work	4	12	--	--	--
Concessions	5	12	72	0	72
BTP/BTT/SIL: BTP (Build to Print)				Total Man-hours	246.4

Time to first article, set up time, machining time:

Plan for 3 attempts, normally scrapped or reworked, before the first deliverable item.

Auto-loading of pallet, total 13 hours m/c time

Could any problems have been foreseen/eliminated by early Manufacturing involvement in design?

-- Yes, all but Report No 2 (which would have needed an early decision to convert the 2D drawings to a 3D model in order to recognise the problem)

Could a better way of making the part have been possible with design changes?

-- Report No 1 showed saving of machine time using 5-axis features.

-- Future designs could be less dependent on tight tolerances for features such as the web thickness, which was very difficult to control

Comments by: Manufacturing, Quality and Design

(see attached reports 1 to 5)

E.1.1 Part A: Arising Report No 1

Category: ☐Engineering Query ■**Engineering Change** ☐Scrap ☐ Re-Work
☐Concession ☐Other (state):

Date raised: -- Date resolved: -- Elapsed wkg days: 12 wks

Nature: To use 5-axis feature in place of using angled cutters in 3-axis, or 5-axis scanning. Manufacturing do not use special cutters due to the cost and difficulty of maintaining them.

Scanning would take three times longer, so the saving would be approx 1 hour machine time per part.

Action to resolve: Proposal was taken to DDP, which met once a month. They would then take the time to consider the merit and give approval.

After approval engineering changes were put in to cover the parts of LR 8-11, 13 and SA 2-5

Design effort to resolve (man-hours): Est 180 hrs for 23 parts = 7.8 hours for Part A

Manufacturing man-hours to address (management/supervisor): 40 hrs for 23 parts = 1.7 hours for Part A

Manufacturing man-hours wasted (production): -

Wasted materials (cost) --

Tooling change (cost) --

Delay to production: Identified early and planned into project time

Comment by Manufacturing: Due to the time taken in the process, this is only possible before NC programming takes place.

Manufacturing feasibility review (with Design, Manufacturing Engineering, NC Programming and Procurement) would have reduced timescale for necessary changes. Once NC Prog completed, it would be much harder to make changes.

Comment by Quality/Inspection: Once the drawing has been changed, the 5-axis 'lump' can be passed off for use in production.

Comment by Design:

See later design process, where generic drawing note covers all manufacturing information (see drawing --).

Modify all existing drawing set, to create generic drawing notes.

(Note: for later designs, Condition of Supply is on drawing, and requires Business Case to change)

Comment by Eng Group Leader, (Site B):

20 or 30 minor changes a week (such as these 23) are currently received, requiring each to be planned into production, up-issue drawings to be read (even if no action required) and process plan changed. Configuration Group also need to note the up-issue. Currently 1 man spends 2 days/week on this.

Relate to PI Table subjects

10, 12, 13, 22, 24, 27

E.1.2 Part A: Arising Report No 2

Category: ■ **Engineering Query** ☐Engineering Change ☐Scrap ☐ Re-Work ☐Concession ☐Other (state): **Not yet submitted**
Date raised: Jul 00 Date resolved: N/A Elapsed wkg days:
Nature: After parts manufactured, some areas noted that were unacceptable to the drawing. Geometry definition does not allow simple 5-axis machining.
Action to resolve: A new geometry needs to be raised and justification needs to be such that it will be worth pursuing to get drawings changed. (Had this been raised with the initial block of 5-axis changes, it would have been resolved then. Now difficult to address.)
Design effort to resolve (man-hours): Estimate 60 hours for 23 parts = 2.6 hours for Part A
Manufacturing man-hours to address (management/supervisor): Estimate 80 hours for 23 parts = 3.5
Manufacturing man-hours wasted (production): 20-30 mins per part in rework (hand blended) = 0.4x 12 = 4.8 man-hours total for 6 sets of two ribs
Wasted materials (cost) -
Tooling change (cost) -
Delay to production: -
Comment by Manufacturing: Difficult to foresee how big the 5-axis 'lump' would be before manufacture, as working from 2D drawings. Need time to develop a possible 5-axis geometry that allows use of standard cutters.
Comment by Quality/Inspection: Part is unacceptable to drawing. Either process changed to meet requirements or standard needs to be changed.
Comment by Design: Create CADDS 5 solid models of each part and programme from the model. Experience on later designs shows similar parts produced with zero queries.
Comment by Eng Group Leader: As for report 1/drawings raised in issue.
Relate to PI Table subjects: Not possible to recognise problem from drawings, so design review with Manufacturing would not have helped.

E.1.3 Part A: Arising Report No 3

Category: ■ **Engineering Query** ☐Engineering Change ☐Scrap ☐ Re-Work ☐Concession ☐Other (state):

Date raised: Various | Date resolved Various | Elapsed wkg days: 1 day to 4 months

Nature:

Problems and errors with drawings, e.g. dimensions missing, notes and pictorial view not matching etc.

11 instances raised total for Part A. For rest of work package average of 2 per part no.

Action to resolve:

WQN raised and submitted to Design for clarification of drawing. Once Design have looked at drawing an answer is issued. (4 of 11 not agreed)

Design effort to resolve (man-hours): Estimate 10 hours per WQN, total 110 hours.

Manufacturing man-hours to address (management/supervisor): Estimate 4 hours per WQN, total 44 hours.

Manufacturing man-hours wasted (production): --

Wasted materials (cost) --

Tooling change (cost) --

Delay to production: Difficult to gauge or measure – NC proceeded at risk

Comment by Manufacturing:

Often the NC program was completed before WQN was answered, first part often manufactured and assumed that other problems would be put right for the next trial.

Comment by Quality/Inspection:

Often TTO report would include reference to the WQN, as the problem with the drawing was known, but this meant that the first part would be held waiting for the reply from Design.

Comment by Design:

Overcome by modelling ribs and creating 2D drawing.

Comment by Design Liaison:

'First article' inspection had been carried out with the original supplier. Previous suppliers all used the same machines and existing NC tapes and tools, and parts were accepted without drawings being updated.

Relate to PI Table subjects:

5, 27 (for CMM)

E.1.4 Part A: Arising Report No 4

Category: ☐Engineering Query ☐Engineering Change ☐Scrap ☐ Re-Work E.1.1.1 ☐Concession ■Other (state): **Extra inspection and potential rework**		
Date raised: --	Date resolved	Elapsed wkg days:
Nature: Web tolerancing expected to be too tight with current process (Note: Design uses web thickness to control weight)		
Action to resolve: Capability studies to take place, decision made after that to challenge whether such a tight tolerance is required. If so, then may be need to modify process to be capable.		
Design effort to resolve (man-hours): --		
Manufacturing man-hours to address (management/supervisor): --		
Manufacturing man-hours wasted (production): --		
Wasted materials (cost) --		
Tooling change (cost) --		
Delay to production: --		
Comment by Manufacturing: This needs to be monitored. A decision can be made only after we get some results after testing. Capability of 5-axis machines not yet fully explored.		
Comment by Quality/Inspection: --		
Comment by Design: Web thickness tolerance required to ensure reserve factors are maintained. Tolerance could be increased positively, but would increase Part weight. Prepared to allow use of General Notes for drawings from later design on this series of parts.		
Comment by (other):		
Relate to PI Table subjects 9, 10		

E.1.5 Part A: Arising Report No 5

Category: ☐Engineering Query ☐Engineering Change ☐Scrap ☐ Re-Work ■ **Concession** ☐Other (state):

Date raised: Various Date resolved: Various Elapsed wkg days: 3days

Nature:

Concessions raised for design features out of position according to general tolerancing specified. Tooling hole tolerance is too tight.

12 concessions in total

Action to resolve:

Quality Inspector would first contact Concession Office to get concession Engineer to make assessment. If likely that concession would be accepted, then query note would be raised and other production operations would be done at risk of concession being refused.

Design effort to resolve (man-hours): Estimate 6 hours per concession, total 72 hours.

Manufacturing man-hours to address (management/supervisor): – Nil (concession paperwork raised in course of normal inspection)

Manufacturing man-hours wasted (production): --

Wasted materials (cost) --

Tooling change (cost) --

Delay to production: Difficult to gauge, as other work was done at risk

Comment by Manufacturing:

Part A is fit for function, but the standard for general tolerancing is not appropriate. It needs to be reviewed. If it is not changed, a technique sheet must be raised to cover the part.

Comment by Quality/Inspection:

While it is accepted that the part will fit and the error will not compromise performance, the standard must be worked. Compared to current supplier, the new parts are closer to the drawing.

Comment by Design:

See later design drawing set, where GD + T applied.

Datum holes have positional tolerance of 1mm (= ±0.5) and are dimensioned from nearest edge, which complies with tolerance standard.

Comment by Eng Group Leader (Site B):

Surprised that this has not been resolved with action from previous suppliers, since this is the 390th set!

Relate to PI Table subjects:

9, 10, 17

E.2 External Supply - Hard metal

E.2.1 Pintle Fitting

<table>
<tr><td>Description of part</td><td>Name
Pintle Fitting</td><td>Size
760x600x170</td><td>Material
Ti</td></tr>
<tr><td>Weight
76kgs</td><td>Assembly</td><td>aircraft/project</td><td>quantity/production rate 1 a/c per month (2 off per a/c)</td></tr>
<tr><td colspan="4">Classification: ☐new/prototype ☒derivative ☐improved version ☐change of manuf</td></tr>
<tr><td colspan="4">☐high volume ☒small batch ☐one-off</td></tr>
<tr><td colspan="2">Designed by: organisation: Company A</td><td colspan="2">Location: Site A</td></tr>
<tr><td colspan="2">Drawing/part number:</td><td colspan="2">Date:</td></tr>
<tr><td colspan="2">Manufactured by: organisation: Company A</td><td colspan="2">Location: Site C</td></tr>
<tr><td colspan="2">Manufacture Release - Inspected by: organisation Company B</td><td colspan="2">Location: Site C</td></tr>
<tr><td colspan="2">Acceptance for Assembly - Inspected by: organisation Company A (paperwork only)</td><td colspan="2">Location: Site B</td></tr>
<tr><td colspan="4">Process (type -- primary/secondary, treatment; new or familiar to manufacturer):
4-axis rough machining of forged Ti billet leaving 3mm finish allowance / heat treat for stress relief / 4/5 axis semi-finish /finish /shot peen /zinc spray /paint</td></tr>
<tr><td colspan="4">Issues raised during Supplier-in-Loop (SIL) working:
-- (serial numbers of Table C.2 issues applying to this part) 4,7</td></tr>
<tr><td colspan="2">BTP/BTT/SIL: SIL</td><td colspan="2">3D CAD modelled? Y</td></tr>
<tr><td colspan="4">Time to first article, set up time, machining time: Total machining time = @35hrs + sets
Note: trial part machined in aluminium.
Questions: was first attempt in Ti successful? Yes
-- Approx how many hours of rework were needed on first successful part? N/a</td></tr>
<tr><td colspan="4">Could any problems have been foreseen/eliminated by ESI in design?
Design of grease nipple hole</td></tr>
<tr><td colspan="4">Could a better way of making the part have been possible with design changes?
If scanned faces had been allowed on angled flange tops, additional 5-axis operation could have been eliminated.
-- what savings might have resulted? Less stages/set ups</td></tr>
</table>

E.2.2 Pylon Bracket

Description of part	Name Pylon Bracket	Size (eg bracket c) 640x600x150	Material Ti
Weight 30kgs (bracket c)	Assembly	aircraft/project	quantity/production rate 1 a/c per month (8 brackets per a/c)
Classification: ☐new/prototype ■derivative ☐improved version ☐change of manuf			
☐high volume ■ small batch ☐one-off			
Designed by: organisation: Company A		Location: Site A	
Drawing/part number:		Date:	
Manufactured by: organisation: Company B		Location: Site C	
Manufacture Release - Inspected by: organisation Company B		Location: Site C	
Acceptance for Assembly - Inspected by: organisation Company A (paperwork only)		Location: Site B	
Process (type -- primary/secondary, treatment; new or familiar to manufacturer): 4-axis rough machining of forged Ti billet leaving 3mm finish allowance / heat treat for stress relief / 4/5 axis semi-finish /finish / assemble sub / 5 axis finish outside profile / disassemble /shot peen / zinc spray / paint / assemble / in-line bore (4 details)			
Issues raised during Supplier-in-Loop (SIL) working: -- (serial numbers of issues in Table C.2 applying to this part) 1,2,3			
BTP/BTT/SIL: SIL		3D CAD modelled? Yes	
Time to first article, set up time, machining time: Total machining time = @35hrs + sets (per bracket) Note: trial part machined in Ti Questions: was first attempt in Ti successful? Yes -- Approx how many hours of rework were needed on first successful part? N/a			
Could any problems have been foreseen/eliminated by ESI in design? Corner rads / ruled surfaces / 5 axis landings			
Could a better way of making the part have been possible with design changes? Manufacturing process problems were averted by early liaison/design changes on the above issues . -- what savings might have resulted? N/a			

E.2.3 Jack Mounting

Description of part	Name Jack Mounting	Size 440x190x230	Material Ti
Weight 18.7kgs	Assembly	Aircraft/project	quantity/production rate 1 a/c per month 2 off per a/c

Classification: ☐new/prototype ☒ derivative ☐improved version ☐change of manuf

☐high volume ☒ small batch ☐one-off

Designed by: organisation: Company A	Location: Site A
Drawing/part number:	Date:
Manufactured by: organisation: Company B	Location: Site C
Manufacture Release - Inspected by: organisation Company B	Location: Site C
Acceptance for Assembly - Inspected by: organisation Company A (paperwork only)	Location: Site B

Process (type -- primary/secondary, treatment; new or familiar to manufacturer):

4-axis rough machining of forged Ti billet leaving 3mm finish allowance: / heat treat for stress relief / 4/5 axis semi-finish /finish / shot peen / zinc spray / paint

Issues raised during Supplier-in-Loop (SIL) working:

-- (serial numbers of Table C.2 issues applying to this part) 5,6

BTP/BTT/SIL: SIL	3D CAD modelled? Yes

Time to first article, set up time, machining time: Total machining time = @14hrs + sets

First tape prove in Ti .

Questions: was first attempt in Ti successful? Yes

-- Approx how many hours of rework were needed on first successful part? N/a

Could any problems have been foreseen/eliminated by ESI in design?

Yes – model should have been created to nominal tolerance for manufacture (lack of 2D drawings to highlight ++tolerances)

Could a better way of making the part have been possible with design changes?

Rad between lug profile and component front edge . Larger rad (i.e. 16.5 or 21) would have allowed the full profile to be rolled . Because of small rad (12mm), alternative method had to be used .

-- What savings might have resulted? Reduced run time and no additional tool requirement

E.3 External Supply: Composites

Description of part Parts C	Name Composite Panels (4 Off Each Hand)	Size From 0.5M to 1.5M	Material Carbon/Kevlar/ and Glasscloth/ Al foil
Weight From 1.5 to 6 kgs	Assembly	Aircraft/project	quantity/production rate 1 a/c set per month

Classification: ☐new/prototype ☒ derivative ☐improved version ☐change of manuf

☐high volume ☒ small batch ☐one-off

Designed by: organisation: Company A	Location: Site A
Drawing/part number(s):	Date:
Manufactured by: organisation: Company B	Location: Site C
Manufacture Release - Inspected by: organisation Company B	Location: Site C
Acceptance for Assembly - Inspected by: organisation Company A (paperwork only)	Location: Site B

Process (type -- primary/secondary, treatment; new or familiar to manufacturer):

Cut material/lay up in mould with pre-formed honeycomb inserts/vacuum bag/autoclave cure/additional lay up and cure of foil layer/ trim perimeter with ICY 5-axis machine/ultrasonic test-inspection /paint

Issues raised during Supplier-in-Loop (SIL) working:

-- (serial numbers of Table D.3 issues applying to this part) 1-13

Arisings See Section D.2.4.5 for details and observations

BTP/BTT/SIL: SIL	3D CAD modelled? Yes

Time to first article, set up time, machining time:

Total manufacturing time = 3 to 8 days per panel

Questions: were first attempts successful? Yes

Could any problems have been foreseen/eliminated by ESI in design? Yes

Could a better way of making the part have been possible with design changes? Yes

Question: would earlier discussion with Design have led to Model build up that was easier for NC programming, tooling and subsequent manufacture? Yes

-- what savings might have resulted? MANPOWER SAVINGS