CRANFIELD UNIVERSITY

SCHOOL OF APPLIED SCIENCES

PhD THESIS

ACQUISITION AND SHARING OF INNOVATIVE MANUFACTURING KNOWLEDGE FOR PRELIMINARY DESIGN

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Abstract

This study investigates the identification, acquisition and sharing of innovative manufacturing knowledge for the preliminary design of complex mechanical components. Such components need to satisfy multiple, often conflicting design and performance requirements. Some degree of innovation may be required, involving the development of new manufacturing processes. The innovative nature of this manufacturing knowledge makes it difficult to define, codify and share, especially during preliminary design, where this can present significant risks in the design process. Current methods of knowledge sharing do not account for the immature nature of innovative manufacturing knowledge and the combined explicit and tacit elements needed to express it.

A flexible interpretive research study with inductive and hypothesis testing elements was undertaken to explore this novel knowledge management problem. During the inductive phase, two data collection activities were undertaken to investigate the manufacturing knowledge required for the preliminary design of gas turbine engines. Using a data driven approach, the main findings which emerged were: the need to include an assessment of the maturity of the design process; the need to use a range of tacit and explicit knowledge to effectively share this and the need to manage knowledge across different domain boundaries. A conceptual framework of the findings was used to develop a hypothesis of knowledge requirements for preliminary design.

For the hypothesis testing phase, a systematic methodology to identify, acquire and share innovative manufacturing knowledge for preliminary design was developed from the knowledge requirements. This approach allowed both explicit and tacit knowledge sharing. An evaluation of the methodology took place using three different industrial cases, each with a different component / manufacturing process. The evaluations demonstrated that using the range of knowledge types for transferring knowledge was effective for the specific cases studied and confirmed the hypothesis developed.

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This thesis is dedicated to the engineers in my family.

Related Publications

1. MOUNTNEY, S. and GAO, J., 2005. Manufacturing knowledge to support preliminary design - a case study, J.X. GAO, D.I. BAXTER and P.J. SACKETT, eds. In: *Advances in Manufacturing Technology and Management: Proceedings of the 3rd International Conference on Manufacturing Research,* 6-8 September 2005, Cranfield University.

2. MOUNTNEY, S. and GAO, J., 2006. Manufacturing knowledge management: requirements for preliminary design. In: P. GHODOUS, R. ROSE DIENG-KUNTZ and G. LOUREIRO, eds, *Leading the Web in Concurrent Engineering: Next Generation Concurrent Engineering.* IOS Press, pp. 515-525.

3. MOUNTNEY, S.L., GAO, J.X. and WISEALL, S., 2007. A knowledge system to support manufacturing knowledge during preliminary design. *International Journal of Production Research,* 45(7), pp. 1521-1537.

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List of Terms and Abbreviations

CE	Concurrent Engineering
KM	Knowledge Management
CAD/CAM	Computer Aided Design / Computer Aided Manufacturing
CoP	Community of Practice
IPT	Integrated Product Team
GA	General Arrangement
APSD	Advanced Propulsion System Design
OBU	Operating Business Unit
DFM / DFMA	Design For Manufacture / Design For Manufacture and Assembly
GE	General Electric
SECI	Socialisation / Externalisation / Combination / Internalisation (model of knowledge generation and transfer)
STEP	Standard for the Exchange of Product model data
CORBA	Common Object Requesting Broker Architecture
CAPP	Computer Aided Process Planning
MFVM	Multiple Feature View Modelling
PLM	Product Lifecycle Management
KBE	Knowledge Based Engineering
EXPRESS	Data modelling language for STEP
UML	Universal Mark-Up Language
XML	Extensive Mark-Up Language
PSL	Process Specification Language
ERP	Enterprise Resource Planning
NPD	New Product Development
Cp Cpk	Process capability indices, measures of process capability
CAE	Computer Aided Engineering
ICT	Information and Communication Technologies
IT	Information Technology
QFD	Quality Function Deployment
R&D	Research and Development
AET	Advanced Engineering Team
LFW	Linear Friction Welding
MFS	Machining From Solid
MCRL	Manufacturing Capability Readiness Level
EIS	Entry In Service
R-R	Rolls-Royce

Chapter 1

Introduction

1.1 Research Background

This study is concerned with the effective identification, acquisition and sharing of innovative manufacturing knowledge requirements between design and manufacture for the preliminary design stage of complex mechanical components.

The terms ‘manufacturing knowledge requirements’ and ‘complex mechanical components’ need to be defined clearly in order to determine the scope of the study, particularly as these definitions can be used in different contexts.

The term 'innovative manufacturing' has up to three meanings. The first describes the development and use of innovative technologies in manufacturing systems engineering in order to integrate and automate aspects of the design and manufacturing processes, thus improving the efficiency of the process. Examples include agile manufacturing, and computer integrated manufacturing (CIM). The second describes the development of new, or improvements in, existing manufacturing processes (Bessant and Tidd, 2007). Examples of such processes are high speed machining (as a development of conventional machining) and direct laser deposition as a method of creating intricate component shapes. The final meaning considers technology management, where the emphasis is on the strategic management of innovation within companies, through mergers and acquisitions and technology transfer from research led institutions into commercial organisations (for examples of research in this area, see Fraser et al., 2002; Farrukh et al., 2007 and Grant and Gregory, 1997). Consequently it is important to define how the considerations of this research study fit into these areas. Essentially it considers aspects of all three meanings.

In this study, innovative manufacturing knowledge is defined as knowledge about a manufacturing process which is undergoing some element of development work within an organisation (second definition). Therefore, some initial research and development work has taken place and some technology transfer has taken place between a research and development department (either internal or external to the organisation) and the process has been proven within that environment. However, the process may not yet have been applied in the organisation, or may have been applied for a different application (i.e. using a different material or component). Further development is therefore required (third definition). Finally, the knowledge about the manufacturing process under development needs to be integrated into the design process in order to mitigate the risks involved in its introduction (first definition).

A complex mechanical product is a component in a large assembly which incorporates mechanical, electrical and software systems. The product is termed ‘complex’ because it is an optimisation of a number of competing engineering requirements. These requirements satisfy multiple operating conditions such as changing static and dynamic forces and environmental conditions. Often, the resulting geometry of the component itself can be complex. Such components are often examples of adaptive design, where a new product is a significant adaptation of an existing product configuration.

Careful management of the design process is required to address the multiple requirements and co-ordinate the emerging design solution. This presents a significant knowledge management challenge. Knowledge about the new product and associated processes may be innovative and therefore difficult to define, categorise or quantify. This situation is further compounded by the increasing need to reduce time to market and consequently manage more risk earlier in the design process.

Pahl and Beitz’s Systematic Design Process is a design process model typically used for and suited to complex mechanical component (Pahl and Beitz, 1988). This process considers design as the successful management of constraints to achieve an appropriate solution which satisfies the relationships between form and function. This is achieved by dividing the process into four stages which sequentially deal with progressively more detailed product knowledge at increasing levels of granularity. The four stages are 1) the clarification of the task, in which the need for a solution is explored and defined; 2) conceptual design, where the solution is defined in terms of a design specification and required functional attributes; 3) preliminary (also called embodiment) design, where an initial realisation of the solution in the form of a engineered product takes place and 4) detail design, where detailed component drawings and production documents are produced.

The successful use of manufacturing knowledge during the design process is essential to realise a successful, cost-effective end product. Historically this has been an area of weakness for the Systematic Design Process. Manufacturing analysis would not take place until the detail design stage, when the geometry of the component had already been largely determined, making changes for manufacturing at such a late stage costly. Using Concurrent Engineering (CE) techniques in the process has alleviated this by enabling manufacturing assessments to take place earlier in the design process. Additionally the staged gate method of managing the process allows the effective management of changes and consultations.

The theoretical definitions of knowledge from the KM community have shaped the development of the tools and techniques for manufacturing knowledge. Two models have been found to be most relevant.

The first model is the data-information-knowledge hierarchy (Young et al., 2004). Data is words and numbers, information is data with context and knowledge is information with meaning. This definition assumes that knowledge is an external commodity which can be move through these states independently of the original source. Therefore a prerequisite to this definition is that knowledge can be coded and is therefore explicit. This model in particular has been used to underpin research into information systems for knowledge management.

The second model was initially proposed by Polanyi and later developed by Nonaka from an organisational perspective (Polanyi, 1966; Nonaka,1994). Organisational knowledge for innovation is created from the combination of knowledge held by the organisational workers. This knowledge can be expressed in explicit and tacit dimensions. Explicit knowledge can be codified, and hence recorded and transmitted. Tacit knowledge is the knowledge which resides 'in peoples' heads' but cannot be easily articulated, hence it is difficult to express and share and not possible to codify. Other research has proposed that knowledge becomes increasingly codifiable as it becomes more mature and quantifiable.

There are two general approaches to knowledge management which are driven by these two theories. The first is the commodity approach which references the data – information – knowledge hierarchy model. This approach is concerned with codifying data and sharing it through the use of information systems. The second approach is the community approach which is concerned with the sharing of tacit knowledge. This approach concentrates on the creation of social networks and other processes to encourage the transfer of tacit knowledge.

When defining knowledge for the engineering design process three things are considered: the content of the knowledge, the theory of knowledge applied and the relevant stage of the design process. The theory of knowledge used has a direct effect on the knowledge content. There are examples of both knowledge theories being applied to defining knowledge for the engineering design process.

Manufacturing knowledge has been defined as knowledge about the process, its capability and cost. Despite the involvement and use of manufacturing knowledge at all stages of the design process, there has been little research to differentiate between manufacturing knowledge required for specific design process stages. The consensus appears to be that such knowledge is 'more abstract' at the start of the project and gains more detail in line with each process stage, although the extent of this abstraction has not been fully defined.

Tools and techniques for managing manufacturing knowledge in the design process mainly follow the commodity approach. They are concerned with the definition, capture, representation and re-use of the knowledge in successive projects. This research area is concerned with transferring manufacturing data across different platforms to make it understood from a design perspective. Examples of techniques used for this are features and knowledge models.

Features have proved to be a popular method of exchanging design and manufacturing knowledge used within CAD/CAM platforms. A feature is defined as a collection of geometry to which some engineering significance can be assigned. Such representation enables knowledge pertaining to that feature to be structured and represented for different lifecycle domains, such as design or manufacturing. However, the domain-specific nature of features limits their ability to be used in knowledge sharing across different domains, even with multiple-view feature modelling, where a different product model is required for each domain. Information models are now the preferred approach for sharing and representing manufacturing and design knowledge. The information is shown in the form of a product model and an additional process model for manufacturing knowledge. Often represented as class-based UML diagrams, the models enable different domains to be modelled and translated. Features are sometimes used in the product structure to represent manufacturing-specific geometry.

Both features and information models require the component to have reached a stage of geometric maturity before they can be successfully applied. Consequently, their most effective use has been at the later, detail stage of the process. In order to be able to define manufacturing knowledge for repeated use, these techniques depend on the knowledge about the manufacturing process itself being fully defined and stable. There has not been any research into situations where the geometry has not yet been finalised and there may be some uncertainty in the process.

A further complication is that the main purpose of features and information model research is to successfully resolve the technical barriers of communicating knowledge across different domain interfaces. Therefore the components used as examples have been deliberately simplified to achieve this. The application of these models to complex mechanical products is therefore another gap in current research.

Research from the management and work psychology communities has criticised the extensive development of information systems tools for knowledge management support, arguing that this has led to an unbalanced focus on explicit knowledge management at the expense of tacit knowledge. Tacit knowledge is required for two reasons. Firstly, innovation (and hence the sharing of innovative knowledge) requires the use of both tacit and explicit knowledge. Secondly, tacit knowledge is also required to share knowledge across different domain barriers.

Examples of techniques which enable the sharing of tacit manufacturing knowledge are Communities of Practice (CoPs) and cross-functional teams. CoPs are concerned with social knowledge sharing within the same domain, whereas cross-functional teams are used for knowledge sharing across domain barriers. The latter has commonly been adopted for the design process as part of CE (concurrent engineering) philosophy, often called IPTs (integrated product teams). However, there has been little research from a knowledge management perspective on these teams. There have been observations made on how the different 'thought worlds' of each domain's can inhibit knowledge sharing (Dougherty, 1992), but little proposed in the form of practical tools and techniques.

This study takes the view that a community approach in itself is not enough to share innovative manufacturing knowledge in preliminary design. There will be an additional requirement to define and codify technical knowledge. An approach which combines elements of both the commodity and community approaches would be beneficial in this situation. There is evidence of approaches being used to define tacit and explicit elements of knowledge in new product design and to explore sharing knowledge across domain boundaries, however such an approach has not yet been adopted for the context of this work.

To summarise, this study has the following novel aspects: it aims to better define the 'more abstract' content and level of the manufacturing knowledge requirements for preliminary design. Of particular interest is innovative manufacturing knowledge, as the main focus with existing research (particularly the commodity approach) is to consider the modelling and knowledge capture of proven manufacturing processes. A combined commodity and community approach to knowledge management has been taken, to ensure that both the tacit and explicit aspects of knowledge necessary to reflect the innovative nature of the knowledge applied. Finally, the study has aimed to develop a practical solution to knowledge identification, acquisition and sharing using the above elements, because there is little evidence of practical approaches being developed in this area, particularly for complex mechanical products.

As a summary of this section, the scope of the study is summarised in table 1.1.

Table 1.1: Scoping of Research

In Scope	Out of Scope
Complex mechanical components	
Adaptive design	Variant and breakthrough innovation
Manufacturing knowledge at component level	Assemblies and interactions between components
Primary manufacturing processes	Secondary and tertiary manufacturing processes
Preliminary design	Other stages of the design process.
Manufacturing processes in development	Legacy components
Identifying, acquiring and sharing 'new' knowledge	Knowledge re-use
Tacit and explicit knowledge	

1.2 Research Aims

The aim of this research study is to investigate the nature of manufacturing knowledge required for preliminary design and how these requirements can be identified, acquired and shared effectively between the specialist design and manufacturing domains. The research is specifically concerned with innovative manufacturing knowledge for the preliminary design of complex mechanical components. It takes place within a collaborating company (see section 1.4).

1.3 Research Design

The research design approach has been determined by the exploratory nature of the research aim. It is flexible and interpretive, with an inductive phase and a hypothesis testing phase. The inductive phase uses semi-structured and unstructured interviews to collect data concerning manufacturing knowledge requirements and qualitative coding techniques for analysis. A hypothesis emerges to describe the requirements for innovative manufacturing knowledge in preliminary design. This hypothesis is then tested through the development of a methodology which is then subjected to a qualitative evaluation using observations and qualitative surveys.

An in-depth appreciation of the design of complex mechanical components was required to undertake a full exploration of knowledge sharing requirements. To achieve this, the study takes place in a single organisation which designs and manufactures complex mechanical components. As such, it is a single critical case because it aptly demonstrates the factors which influence the design of these components. The rationale for this is to yield results and conclusions from this specialised case with the intention of contributing to the overall knowledge in this area.

The next section introduces the organisation selected as the critical case and outlines the context of the research undertaken.

1.5 Research Context

Rolls-Royce plc designs and manufactures gas turbine engines for military and civil aviation, industrial and marine applications. It is the second largest UK aerospace company (after BAE Systems), employing around 38,000 people across fifty sites worldwide. It is currently ranked the world number two engine producer after GE and is number one in large turbofans.

The research for this thesis took place over a three year period at the organisation's Derby site, which is the headquarters of the civil aviation business. The main engineering and manufacturing operations are based at this site and cater for the majority of stages within the product lifecycle. They are also supplemented by sales and marketing and in-service support divisions. The focus of this research is the design process for new gas turbine engines from the Trent family of products, which have a 50% market share in their sector.

It must be noted that the organisational research took place at a certain point in time. The remainder of this section outlines the design processes and organisational structures which were in place at the time of the study and as such contributed heavily to the research findings. Such processes and structures may have since undergone changes or improvements.

The Trent family of aviation engines are variants of a three-shaft compressor and turbine configuration. This configuration was first developed nearly forty years ago with the RB211, originally developed for the Lockheed Tristar and used on the Boeing 747. Subsequent products include the Trent 500 (developed for Airbus), Trent 800, Trent 900 (Airbus A380) and Trent 1000 (Boeing 787). Each engine development is tailored specifically to the range and requirements of the aircraft.

The gas turbine engine is a complex systems integration of mechanical, electrical and software systems. The main systems are the compressor, combustion and turbine, the transmissions systems and auxiliary power systems. As an original equipment manufacturer, the company is responsible for providing the complete system to the airframe manufacturer.

The components which are integral to these systems are suitable examples of complex mechanical components for the following reasons. Firstly, the gas turbine engine is subject to a number of requirements essential from an operational and environmental point of view. The weight must be minimised for maximum fuel efficiency. The thrust, power and fuel consumption requirements dictate the temperatures and speeds at which the engine is run. Secondly, the resulting in-service environment is an essential consideration in the engine design. The resulting component configurations are complex in shape, for example a turbine or compressor blade. This presents challenges in terms of dimensioning and tolerancing and stress analysis. The manufacturing knowledge required for these components will be complex, reflecting the design situation. It may take a number of forms, may be uncertain and not that easy to codify.

The design process for the gas turbine engine needs to be systematic to address all the required design variables. The product configuration and maturity need to be tightly controlled at all stages of the process with a rigorous sign-off procedure and change management process. This is managed using a staged gate process with a gated review process at the end of each stage.

The product introduction process for civil engines is referred to as the 'Derwent Process' and is analogous with Pahl and Beitz' systematic design approach. There are four stages with gate reviews at the end of each stage. Stage 0 is the Concept stage, in which a performance cycle is produced. This specifies the performance requirements and functions for the engine based on customer specification. Stage 1 is early preliminary design, where an initial mechanical design solution which satisfies the performance cycle for the whole engine is produced. This is shown as a 2D General Arrangement (GA). Stage 2 is also preliminary design and is the optimisation of each of the major sub-systems of the engine: the compressor, combustor, turbine and transmission. Detailed component design and optimisation takes place during this stage, including manufacturing optimisation. Finally in stage 3, detailed production layouts are produced to enable manufacturing to commence.

As the product matures, the number of people in the design process increases. Stages 0 and 1 are carried out by a small central team known as APSD (Advanced Propulsion System Design). From stage 2 onwards, the design of each major sub-system and its components is handed over to an Operating Business Unit (OBU) responsible for that system. Each business unit contains 200+ design and manufacturing engineers. Stage 1 involves some collaboration between APSD and each of the OBUs. Design iterations take place and the GA is updated accordingly. At stage 1 exit, the engine design is effectively handed over to the sub-system business units, who then own the design and manufacture of their system.

The concurrent engineering ethos is built into the design process in a number of ways. The gate review process by its very nature ensures that multi-disciplinary collaboration takes place during the design process. Formal approaches to concurrent engineering take place from stage 2 onwards through Design For Manufacture (DFM) sessions and the use of Integrated Product Teams (IPTs) for specific components. The former creates a forum in which the detail design of a component can be examined against manufacturing criteria for cost savings. The latter creates a forum where conflicting design issues can be examined. Manufacturing is represented alongside other disciplines. Design and manufacturing engineers for specific component families are co-located in the same OBUs.

Unlike stage 2 and beyond, stage 1 of the design process does not appear to have any formalised support tools for sharing manufacturing knowledge. It is evident that some exchange is taking place at this level, but further investigation is required to define the knowledge required.

Different information system support tools are used at different stages of the design process. Many tools have been developed in-house to meet the specific requirements of the process at that particular stage.

The main output of stages 0-1 is the first mechanical engineering schematic of the engine project. This is represented as a whole engine in 2D with the main dimensions and coordinates shown. The General Arrangement (GA) is then passed to the Operating Business Units for stage 2, which is carried out by 3D modelling. Some business units have carried out experiments with feature-based design using ‘standard features’ with inherent manufacturing capability, although the most success has been found with the later, detail stages of design. Other tools used include knowledge-based engineering systems for optimising the engineering of certain components, intranet-based reference material and reference folders which contain the main recorded documentation on specific engine projects.

The advent of digital technology has greatly reduced the lead time for a new airframe. In line with their main competitor GE, Rolls-Royce now advocate a 24 month development time for a new engine.

Simultaneously, legislation is continuously adding further restrictions to noise and emissions and increasing fuel efficiency. Consequently engines need to be designed to run at higher speeds and temperatures, creating a need for new materials, coatings and treatments and manufacturing processes which can deliver them. The design envelope of the three-shaft turbine engine is being stretched to its limits in order to incorporate these requirements.

By combining these two factors – more development in a shorter lead time – it can be seen that the risk in new engine introduction is increasing, especially in the introduction of new manufacturing processes. When should these be assessed? The existing design process caters for this in stage 2, however DFM will only examine the final details, not the primary process. If a major problem is found during stage 2 then it will be costly in terms of time and finance to resolve. It is clear that such issues need to be resolved earlier in the design process, i.e. before stage 2.

1.6 Thesis Structure

Chapter 1 Introduction

This chapter introduces the research background and context, discussing the research aims and the thesis structure.

Chapter 2 Literature Review

This is a literature review chapter which investigates research in knowledge management requirements, techniques and tools. The topics covered are definitions of knowledge, definitions of manufacturing knowledge and techniques for sharing manufacturing knowledge. Research gaps are identified and discussed.

Chapter 3 Research Objectives and Methodology

This chapter identifies the research objectives resulting from the gaps identified in the literature review. The research design approach to achieve these objectives is then introduced.

Chapter 4 Innovative Manufacturing Knowledge in Preliminary Design

This chapter documents the first of two data collection activities for the study, an investigation into the nature of manufacturing knowledge for preliminary design using semi-structured interviews. A grounded theory analysis was used to develop a conceptual framework of the knowledge requirements for preliminary design and the types of knowledge needed to represent them.

Chapter 5 Investigation into Manufacturing Knowledge for Blisks

This chapter demonstrates the second data collection activity for the study. This was an exploration of the manufacturing knowledge requirements for an innovative manufacturing process using unstructured interviews and a review of company documentation. This activity resulted in a more detailed understanding of the acquisition and sharing of knowledge for the type of situation which emerged as being of particular importance during the first data collection.

Chapter 6 Development of a Methodology for Effective Knowledge Sharing

In this chapter, the findings from the two collection activities are developed into a systematic methodology for the identification and effective sharing of manufacturing knowledge requirements during preliminary design.

Chapter 7 Evaluation of the Methodology

This chapter documents the qualitative evaluation of the methodology using three different components and processes. The results are analysed and discussed.

Chapter 8 Discussions, Conclusions and Future Work

This chapter discusses key findings, contributions to knowledge, research limitations and recommendations for further work.

This structure is illustrated in figure 1.1.

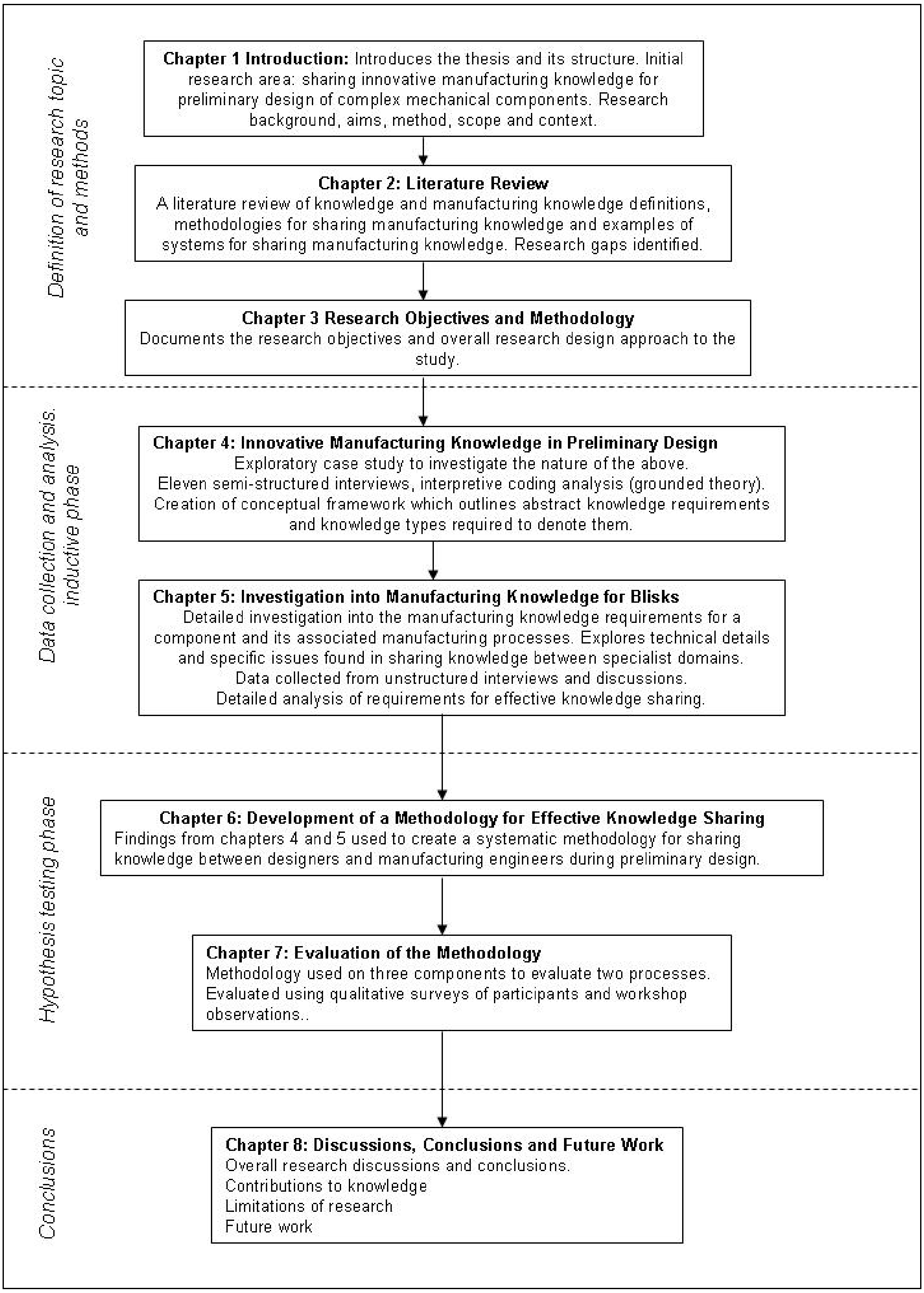


Figure 1.1: Structure of the thesis

Chapter 2

Literature Review

2.1 Introduction

This chapter reviews and discusses the academic literature relevant to the research aims and themes. It highlights the research gap to be addressed by the thesis.

The literature review is concentrated on three topics which are central to the study and its context. These are knowledge sharing, the preliminary stage of the engineering design process and manufacturing knowledge. Around 250 papers have been reviewed, with those most relevant discussed in this chapter. These papers are from the fields of knowledge management, information systems and business management research, the majority having been published since 1990.

Firstly, some theoretical considerations of knowledge were explored as a foundation for the remainder of the review. These were the theoretical definitions of knowledge, approaches to knowledge management and approaches to knowledge sharing. A particular interest in this part of the review was the treatment of innovative technical knowledge. The engineering design process was then investigated as the theoretical background to the study. Of particular concern was the definition of the preliminary design stage and how this differed from other stages of the design process. Next, manufacturing knowledge and its application in the engineering design process was reviewed. Two angles were explored. The first was the content of manufacturing knowledge and how this differs depending on the stage of the design process. The second was how it has been defined in practice and how the theoretical definitions of knowledge have been applied in this context.

Approaches to knowledge sharing were then investigated, with the emphasis on practical examples relating to the engineering design process and the sharing of manufacturing knowledge. The preliminary design stage was explored along with other stages, again to compare and contrast the use of manufacturing knowledge. The suitability of these approaches in incorporating technical innovative knowledge were also considered.

Key observations from each part of the review produced a series of research gaps for the sharing of innovative manufacturing knowledge during the preliminary stage of design. To conclude, these gaps are outlined together with the decision for the focus of the study.

2.2 Knowledge Management and Definitions of Knowledge

The study of Knowledge Management within the organisation is a relatively new subject area, dating from the early 1990s. However, some of the philosophical references date back to the discussions of Plato and Socrates (Alavi and Leidner, 2001). Other more recent philosophers have also added to the debate, especially in (Polanyi, 1966) who underpins much of the theory in organisational knowledge creation originated in (Nonaka, 1994).

Knowledge Management as a subject of study and practice arose as a consequence of the definition of the Knowledge Economy. This concept states that the value of the organisation lies not within the commodities (product or service) that it produces, but within the knowledge applied within the organisation to produce it. This has become increasingly important during the birth of the digital age and the internet, where the commodity has become less tangible, yet an embedded knowledge value is inherent (Alavi and Leidner, 2001).

Several definitions of knowledge have arisen within the knowledge management discipline. The origin of the definition depends on how knowledge is categorised and can consequently affect the way in which it can be used (Alavi and Leidner, 2001).

The three most popular and cited definitions are the data-information–knowledge hierarchy, tacit and explicit knowledge and declarative and procedural knowledge. Each of these definitions will be discussed in turn.

2.2.1 Data – information – knowledge hierarchy

A typical definition is found in (Young et al., 2004). Data is text or numbers. Information is data with added context to explain the data. Knowledge is the interpretation of information in order to assign meaning. Initial observations can therefore be interpreted as data, context added to give the facts and ultimately interpreted at a higher level as knowledge. A hierarchy is created where data and information become lower level pieces which create the building blocks for the next level (information and knowledge respectively). This interpretation presents the idea that knowledge can be reduced to blocks which can be coded, shared and used. Consequently, this definition has originated from and is mostly used for developing information systems for knowledge management.

2.2.2 Tacit and explicit knowledge

Tacit and explicit knowledge were originally defined in (Polanyi, 1966). Explicit knowledge can be articulated and represented as a formal language (codified). Consequently it can be shared between sources without losing its integrity. Tacit knowledge is rooted in an individual's own personal experience and beliefs and has two components. The first is a technical component, which is the knowledge which is demonstrated in practical skills such as craft. The second is a cognitive element from the individual’s own beliefs and viewpoints. The personalised nature of tacit knowledge makes it more difficult to express, codify and therefore share.

Polanyi's concept of knowledge with tacit and explicit components has been adapted and popularised mainly through the work of Nonaka, in which knowledge is defined as being a 'justified true belief' (Nonaka, 1994). Information is defined as the flow and exchange of messages. These messages have syntactic and semantic aspects. These are concerned with information capture and attributing meaning respectively. The latter is important in creating organisational knowledge. Furthermore, the organisational knowledge itself is created by the exchange of knowledge in its tacit and explicit elements (Nonaka, 1994).

This definition is fundamentally different from the data – information – knowledge hierarchy knowledge. Knowledge is seen as residing in and originating from individuals within the organisation. It is this combination of business-specific individual knowledge which forms the collective knowledge of the organisation. Therefore knowledge may have explicit or tacit (and often both) elements at any time, but it is not a commodity which exists independently from its creators. Explicit knowledge may be captured and represented in a database, however the data itself needs to be interpreted and understood within the context of the organisation (tacit knowledge) so that it may be used successfully.

2.2.3 Declarative and procedural knowledge

The tacit and explicit components of knowledge are useful in an explanation of the nature of knowledge and how it can be defined, transformed, transferred and applied. However, the third definition has a more pragmatic approach. Here knowledge is defined in terms of its source and its application and is categorised as being declarative, procedural or causal (Zack, 1999). Declarative knowledge, or ‘know-what’ is the content of the knowledge. Procedural knowledge, or ‘know-how’, refers to the processes necessary in the use of the knowledge. Causal knowledge, or ‘know-why’ refers to the underlying recognition of where it is appropriate to apply the knowledge. Zack recognises the tacit element of knowledge but declares that the above can be and should be made explicit in order to obtain the maximum organisational benefit. The nature of the knowledge can range from being broad (and consequently easier to codify and share) to specific, in which context becomes important and definition and codification is more difficult unless there is a common domain.

2.2.4 Comparison of the theories

Research has attempted to compare and contrast these three theories and to examine the links between them. Although Zack's definition is treated here as a separate theory it does draw on and include some elements of the first two. However, no universal understanding has emerged and each research perspective has yielded an individual response.

Tuomi's research is critical of the data - information – knowledge hierarchy model, asserting that it does not truly address the complex nature of knowledge. In order to derive knowledge from data, some initial knowledge of that context of data in the world must first be appreciated. A reverse hierarchy model is presented as an alternative. In this case, data is the end point of a transformation process rather than the start. The act of adding structure to knowledge to produce information and data externalises and codifies that knowledge, thus creating explicit knowledge. A link is established between the hierarchy and the tacit / explicit dimension (Tuomi, 1999).

Hicks et al, in their work to illustrate knowledge types and methods for management, also assert that knowledge does not behave in accordance with the data-information-knowledge approach. Their belief is that data can be transformed into knowledge and knowledge can become data when used in another domain. Other components such as behaviour aspects, organisational knowledge and learning are also missing from the hierarchy. They therefore present an alternative which incorporates both the data-information-knowledge approach and the tacit / explicit definition can be seen in (Hicks et al., 2007). Their model, Explicit Islands in a Tacit Sea (EITS), again draws on Nonaka's tacit / explicit model. Explicit knowledge heads the model because, like Zack, it is seen as being the most important. The data component is acknowledged as being larger. Bridges between these support a two-way transformation of knowledge. The 'sea of tacit knowledge' exists to enable the creation of data, information and explicit knowledge and to select the tools for best practice. The model is designed to support the main models defined. However, it remains a concept representation and does not seem to add anything in addition to Tuomi's work (which has greater citations) and Nonaka's SECI model (see section 2.4).

2.3 Knowledge and Innovation

Within the Knowledge Management discipline, the generation and use of knowledge for innovation is seen as being necessary for organisational success and therefore pivotal to the Knowledge Economy (Grant, 1996). This section reviews how some researchers have considered knowledge for innovation in relation to the definitions of knowledge discussed in section 2.3.

Nonaka's theory of organisational knowledge creation is concerned with the creation of organisational knowledge for the purposes of innovation. Here, innovation is defined as a process in which problems are defined within the organisation and knowledge sought to solve them (Nonaka, 1994).

Knowledge must move between tacit and explicit states for the creation of organisational knowledge. This is illustrated by the SECI model which has four interacting mechanisms of explicit and tacit knowledge which are generated in a continuous spiral. Knowledge is initially created by *socialisation* (a tacit to tacit knowledge transfer); then *externalisation*, where this knowledge is codified (tacit it to explicit); *combination*, where explicit knowledge is transformed into other formats of explicit knowledge and finally *internalisation*, where explicit knowledge is absorbed to become tacit knowledge. The tacit element is at the heart of the knowledge, but this must be interpreted using the explicit element. Furthermore, both knowledge elements need to interact in order to build this knowledge creation. There can be limitations to the creation of and use of new knowledge if it remains in the same state.

Senker’s discussion paper on tacit knowledge and innovation also references Polanyi but pre-dates Nonaka’s work (Senker, 1993). Her particular interest is in the methods used to capture *‘tacit knowledge of a scientific and technological nature’* within and outside the organisation. In a study based on industry and university links for biotechnology, advanced engineering ceramics and parallel processing, she investigated how tacit knowledge contributed to innovation activities, whether it could be codified and whether it had limitations. She found that although science tended not to acknowledge tacit knowledge and skills, much tacit knowledge was involved in learning about science, its analysis and scientific research. Technology firms acknowledged it more. Like Nonaka, she found that an important factor in sharing tacit knowledge was interdisciplinary personal interaction, noting that *‘both scientific and technological inputs to innovation embody a considerable tacit component which can only be acquired by practical experience.’*

She identified four reasons why tacit knowledge was important: it improves learning; it is used to solve technical problems; it is a necessity for understanding the complexity of systems and it is fundamental for new emerging technologies. She also identified three main routes to the codification of tacit knowledge: the science push, where theoretical underpinnings are applied; the technology pull, where industrial problems are explored and automation (although this was limiting for innovation).

Bohn also explored technological knowledge (defined as the knowledge associated in realising products and services) and its tacit and explicit elements (Bohn, 1994). A third dimension – that of knowledge maturity - is introduced. A scale of knowledge maturity is proposed in which knowledge types are used to describe the maturity of a process. Process maturity is defined as the ability to which its attributes can be codified and standardised (see table 2.1).

Bohn takes a pragmatic view of industry, claiming that any organisation will have a mix of processes at varying levels of knowledge maturity, which will in turn affect learning, problem solving, production and job roles. Therefore a mix of approaches and methods should be used for successful management (summarised in table 2.2). This is seen as particularly important in high-tech industries, as *'managing in high-tech industries requires both rapid learning and the ability to manufacture with "immature" (low stage of knowledge) technologies.'*

Table 2.1: Knowledge types and Process maturity (Bohn, 1994)

Stage	Name	Comment	Typical form of knowledge
1	Complete ignorance		Nowhere
2	Awareness	Pure art	Tacit
3	Measure	Pretechnological	Written
4	Control of the mean	Scientific method feasible	Written and embodied in hardware
5	Process capability	Local recipe	Hardware and operating manual
6	Process characterization	Tradeoffs to reduce costs	Empirical equations (numerical)
7	Know why	Science	Scientific formulae and algorithms
8	Complete knowledge	Nirvana	

In some ways Bohn's view is positivistic. It appears to infer that everything should be measurable and that qualitative data is inferior to quantitative. In table 2.2 there is a link between artistic learning and process immaturity, which may not necessarily be the case. Nonetheless, it is an interesting application of the explicit – tacit definition to a potentially time-based maturity scale of knowledge. It also has interesting implications for the context of this research. Manufacturing knowledge may not be a straightforward case of defining specific content. It may change and evolve over time depending on the ability of the process to be codified.

Table 2.2: Knowledge stages and learning approaches (Bohn, 1994)

Knowledge at stage	1 2	345	678
Nature of production	Expertise based		Procedure based
Role of workers	Everything	Problem solving	Learning and improving
Location of knowledge	Workers' heads	Written and oral	In databases or software
Nature of learning	Artistic	Natural experiments	Controlled experiments, simulations
Nature of problem solving	Trial and error	Scientific method	Table look-up
Method of training new workers	Apprenticeship, coaching		Classroon
Natural type of organization	Organic	Mechanistic	Learning oriented
Suitability for automation	None		High
Ease of transfer to another site	Low		High
Feasible product variety	High	Low	High
Quality control approach	Sorting	SPC	Feed forward

Saviotti's study investigates the relationship between codification and the appropriability of knowledge (Saviotti, 1998). Although the scope of the paper is in acquiring knowledge within academic disciplines, some points are found which reflect the findings of Bohn, Nonaka, Zack and Senker. He defines knowledge as a being a *'correlation structure'* as it is used to establish the relationships between variables. Like Bohn, he claims that 'new' knowledge tends to be more tacit in nature, becoming more codifiable as the discipline matures. The codification process is seen as being necessary to transform the knowledge from people's head into a form that can be communicated.

2.4 Key Observations

Knowledge has been interpreted in several ways, however some similarities exist between the definitions. All three definitions indicate a codifiable perspective to knowledge where it is easy to articulate in a shared context.

A common emerging theme is that of sharing information. Alavi and Leidner stress that a knowledge management system must be able to capture the knowledge bases of individuals yet assign meaning which is relevant for the organisation (Alavi and Leidner, 2001). Fahey and Prusak also highlight the importance of creating a 'shared context', which they define as an understanding of the world of the organisation as seen by the shared *'world views'* of the individuals (Fahey and Prusak, 1998). As these 'individual's world views' are the basis of their decision making, it is necessary to establish a common context to enable knowledge to be *'an activity that brings individuals to deeper understanding through dialogue'*. Nonaka and Grant see organisational knowledge as being the combination of elements of individual knowledge for the benefit of the organisation (Grant, 1996; Nonaka, 1994). Tuomi acknowledges that establishing a shared understanding between individuals can be difficult as *'the original articulator and the sensemaker need to have overlapping meaning structure. One could say they have to share some world where the data can make sense'* (Tuomi, 1999).

The need for the shared context governs the appropriate knowledge type. Leidner and Alavi support the uses of both tacit and explicit knowledge as they are mutually dependent and reinforce each other. This point is reinforced by Nonaka's SECI model. Zack stresses that tacit knowledge should be made explicit because it is only then that knowledge can be a competitive advantage. Fahey and Prusak see tacit knowledge as being fundamental to the creation and use of explicit knowledge. Tuomi proposes ways in which tacit and explicit knowledge could be exploited for different purposes. The strength in explicit knowledge would be in articulating and codifying routine operations in a shared context. Where the context is not as shared, the exploitation of tacit knowledge through a social approach is proposed.

Another emerging theme is the importance of tacit knowledge in the generation of innovative knowledge (Senker, 1993). However, it must be combined with explicit knowledge in order to generate innovative knowledge (Nonaka, 1994), or be increasingly codifiable as it matures (Bohn, 1994; Saviotti, 1998).

What emerges from the research is how the definition of knowledge governs the way in which it can be represented and managed.

Two main approaches are adopted in knowledge management. The first is concerned with codifiable knowledge and the development of a mainly information system-based perspective in supporting this. The second is a more social perspective evident where knowledge is not so easy to articulate and a shared context needs to be established in addition to the knowledge. These two diverse approaches are referred to as the 'community' and 'commodity' approaches (McMahon et al., 2004). Their definitions are important to this study because they define the two main ways in which knowledge sharing methods have been applied practically for the context of this thesis. A comparative analysis of these two approaches takes place in sections 2.7, 2.8 and 2.9.

2.5 Knowledge in the Engineering Design Process

The theories of knowledge and knowledge management are applicable to the design process. Hicks et al refer to the engineering design process as an *'information transformation process'* (Hicks et al., 2002). The decisions necessary to move a design from one state to the next are driven by knowledge and information. Therefore it is important to consider the stages of the design process and the content and nature of manufacturing engineering knowledge. It is also important to explore how the theoretical definitions of knowledge discussed in section 2.3 apply to this particular situation.

2.5.1 Content

Pahl and Beitz' systematic approach to engineering design defines the design process as managing the constraints from a number of factors to produce the best solution (Pahl and Beitz, 1988). A successful design solution will satisfy the relationships between function and form.

There are three stages to the design process: concept, preliminary (also termed embodiment) and detail. The concept design stage is concerned with the product function. During this stage the intended functions of the product and potential solutions to achieve them are explored. The outcome of this stage is a defined list of product targets which the solution is expected to achieve. The preliminary design stage is concerned with the relationship between function and form. The requirements and functions finalised during the concept stage are transformed into an initial engineering general arrangement (i.e. a physical representation) during this stage. The detail design stage is concerned with the detail form of every component in the product. The arrangement from the preliminary stage is optimised and finalised, each part is fully defined (including geometric dimensions and tolerances), the final material selection takes place and the product is assessed for technical and economic viability. The necessary documentation is also created to enable the product to be produced and maintained.

The authors also differentiate between different types of design. An original design is a completely new solution and product. An adaptive design will satisfy an existing solution in a new way (therefore requiring new or substantial changes to existing components and possibly assemblies). Variant design is the modification of an existing product to meet the same solution. The emphasis on each stage of the design process may change according to the type of product being considered. A large one-off or adaptive product will feature all the stages, but will need to build in controls along the process to manage the risk, particular if there is an element of innovation involved.

The preliminary stage is of specific interest to this thesis. This stage of the process is signified by the following characteristics. It has multiple design activities running concurrently. These activities can be interdependent – a change in one area will require a number of changes in other areas. Some activities will need to be worked at a higher level than others, however 'higher level' knowledge is not defined. The process has the following steps: identifying the requirements which have the main influence on the overall design, the requirements which affect the overall size, the requirements which affect the overall arrangement and the requirements which may affect the material selection. Other requirements – safety, ergonomics and production will affect all these factors. There are two preliminary design stages. These are summarised in figure 2.1 (Pahl and Beitz, 1988, p. 41)

The designer is encouraged to reduce risks in the design as far as possible and also to 'design for production' which is defined as being able to maintain quality at the lowest possible cost. Consequently, the production impact is seen primarily as a cost impact. Production is defined as knowledge about manufacturing processes, assembly, quality, materials handling and operations planning. Pahl and Beitz do not relate the level and content of manufacturing knowledge directly to the stage of the design process. Rather, it is linked to particular activities. Table 2.3 (reproduced) summarises the factors which need to be considered by design and product. As the overall layout design is primarily the concern of the preliminary stage, perhaps the production considerations for that activity are relevant. However, there are no guidelines for the content and level of knowledge to be communicated at that stage.

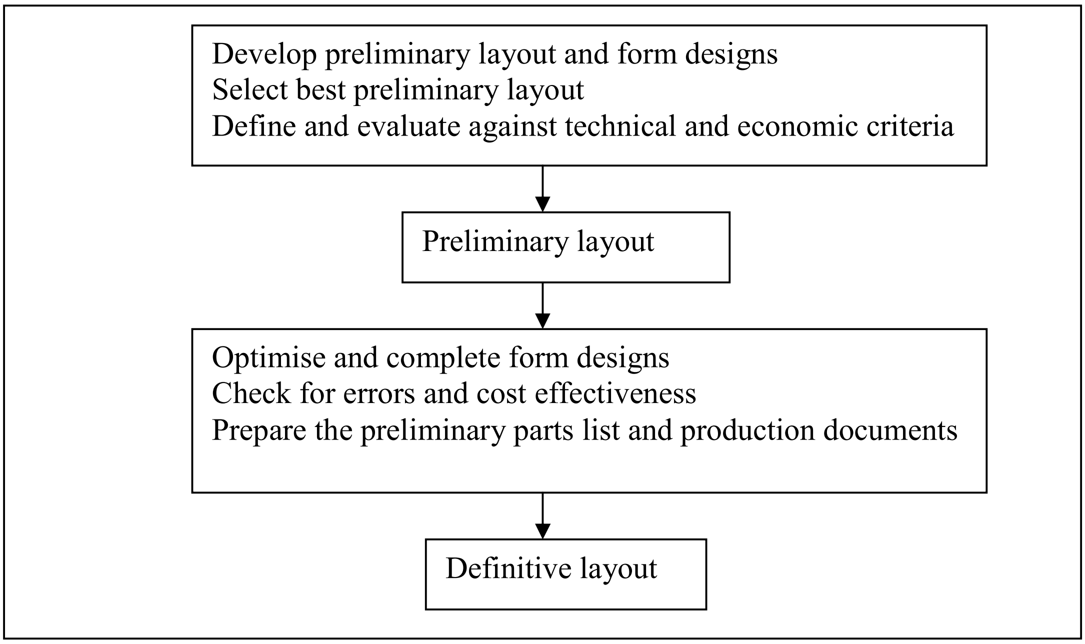


Figure 2.1: The Two Stages of Preliminary Design (Pahl and Beitz, 1988, p.41)

Table 2.3: Relationship between Design and Production (Pahl and Beitz, 1988, p.266)

	Design considers:-	Production considers:-
Overall layout design	Assemblies Components Bought-out parts Standard parts Joining and assy Transport aids Quality control	Production procedure Assy and transport possibilities Batch size of similar components Proportion of in-house and bought-out items Quality control
Component form design	Shapes and dimensions Surface finishes Tolerances Limits and fits	Production procedure Manufacturing methods, machine tools Measuring instruments In-house and bought-out components Quality control
Materials selection	Type of material Treatment Quality control Semi-finished materials Availability	Production procedure Manufacturing methods, machine tools. Materials handling (purchase, shape). In-house and bought-out parts. Quality control
Standard and bought-out components.	Repeat parts Standard parts Bought-out parts	Purchase Storage Stock control
Production documentation	Workshop drawings Parts list Data processing programmes Assembly instructions Testing instructions	Execution of orders Production planning Production control Quality control

The DFMA (Design for Manufacture and Assembly) methodology originated to enable greater consideration of production and assembly requirements before the detail design stage (Boothroyd et al., 2002). The aim is to design products which are easier to manufacture and assemble which can consequently be produced at a lower cost. Examination of suitable manufacturing processes is again encouraged early in the design process as a process selection needs to have taken place in order to progress to the detail design stage. As with the systematic approach, process also needs to be considered in conjunction with the material. The tools in the methodology are aimed at creating a teamwork approach.

During material and process selection, the product attributes need to be matched to the capabilities of the process to meet them. There are three process types: the primary process, which initially creates the product shape and ideally satisfies as many product attributes as possible; the secondary process, which is used to create the main shape, features and refined features and the tertiary process which is used to generate product properties rather than shape. There is no differentiation of manufacturing knowledge requirements between different stages of the process.

A practical application of the DFM methodology is seen in (O'Driscoll, 2002). With this application a number of checkpoints were built into the existing design process to ensure that the required knowledge had been supplied. Their design process does not fit the model of Pahl and Beitz but does have some similarities. There are three stages of increasing detail – definition, development and validation/scale up. Initial process list and performance indices (process capabilities) are considered from the definition stage. The type of manufacturing product considered was not discussed.

Lovatt and Shercliff also considered process selection in mechanical engineering design, the main driver again being minimum cost assuming all relevant technologies are available. Again the importance of the process and material link is established, but also linked to governance of shape. They do however note that in practice the shape is usually decided first. They note that material selection is often based on technical considerations, however the considerations for production are usually economic (Lovatt and Shercliff, 1998a).

Chen investigated extending the DFMA methodology to improve support for designers, noting that they often lacked the relevant experience and knowledge to make information decisions about process selection (Chen, 1999). Again, the influence of process, material and shape was acknowledged.

The research looked at production feasibility (the capability of the process to meet design attributes) and cost. For the earlier stages of the design process, this was seen as a 'screening out' process for unsuitable processes rather than a calculation. The manufacturing information to be used was phase-specific and depends on the design information which is available during the phase. A conceptual framework for a manufacturing decision support system was developed, which was in essence about *'information interaction between designers and manufacturing engineers'* and its components. A case study example was created using machining as an example, and the research did not acknowledge the tacit and explicit elements of knowledge. The research re-iterates the themes identified so far: where knowledge comes from (the individual) and how it interacts. This research considered knowledge from another domain being framed so that it could be accessed by another domain.

Nowack specifically explored the assessment of 'manufacturability' during the early stages of the design process, developing guidelines to assist in initial assessments (Nowack, 1997). Manufacturability was defined as being a capable process to meet the product attributes.

All the references refer to the relationship between the product form, the material and the process in process selection. They also stress the need to convey information about the process, its capability and its cost. The desired situation is that the manufacturing process is mature and stable in that it has a known capability that matches the product attributes. There is no information on how to handle innovative manufacturing processes and their associated risks. Also, the manufacturing knowledge for each stage – its content, the level required and the best ways to involve the design and manufacturing functions – has not been defined in detail.

2.5.2 Comparison with knowledge management definitions

The data / information / knowledge interpretation of knowledge has been adopted in (Hicks et al., 2002) for creating a framework to relate information and knowledge. The need for explicit information and the importance of representing this electronically is certainly acknowledged. Although they do not reference Nonaka or any other research on tacit and explicit knowledge, they also acknowledge that such explicit information needs additional support and interpretation from designers' own experience and knowledge. Information is interpreted as being either formal or informal. Formal information is structured and can be represented. Informal information is less structured and usually obtained from discussions. Knowledge is inferred from information, the preference being towards informal information. Because of its unstructured and personalised nature, informal knowledge is seen as being possibly unreliable due to bias.

An example of the use of the declarative / procedural approach to knowledge can be seen in research by Fu et al, who investigated the knowledge content required for design in the aerospace industry (Fu et al, 2006). They carried out research to determine the knowledge content required for design. The results were high-level and categorised into market, human, technology and procedural knowledge. However, the resulting categories did not include manufacturing or production knowledge.

Both examples demonstrate that within engineering design, content and knowledge form are inextricably linked. This has been developed by (McMahon et al., 2004) to demonstrate how the knowledge form can influence the type of support systems used.

They discuss the personalisation (tacit) and codification (explicit) definitions of knowledge, linking this with the community and commodity approaches to knowledge management. The product type itself is also presented as a major influence on the suitability of the approaches. The commodity approach, which promotes the capture, use and re-use of knowledge, is presented as being advantageous for standardised, mass-produced products. Conversely, the community approach is suited to customised products. However, the need for both approaches is acknowledged in the engineering design process.

A number of approaches to knowledge management are then reviewed and rated on a scale of suitability for personalised vs. codified knowledge in the context of aerospace and automotive industry applications. The output of this is shown in figure 2.2.

Other research has also considered the tacit and explicit components of knowledge, for example when analysing the product development of automotive products (Ferrari and Toledo, 2004). The tacit nature of production in particular is also highlighted in (Grant and Gregory, 1997) because it requires a wide range of knowledge from a number of different people.

Research into the Hong Kong jewellery industry also has interesting results concerning tacit and explicit knowledge (Siu and Dilnot, 2001). The research was carried during the transition of the industry from being mainly highly-craft based to mass production. During the transition three points were noted. The first was that experience and knowledge previously carried out by artisans was segregated into design and manufacturing specialisms, resulting in some loss of tacit knowledge. The second was that the artisans needed to adapt their skills in order that new digital technology could be used successfully during the design-make process. Thirdly, the full extent of the artisan's tacit knowledge and skills could not be successfully coded into a digital system, particularly in initial model-making.

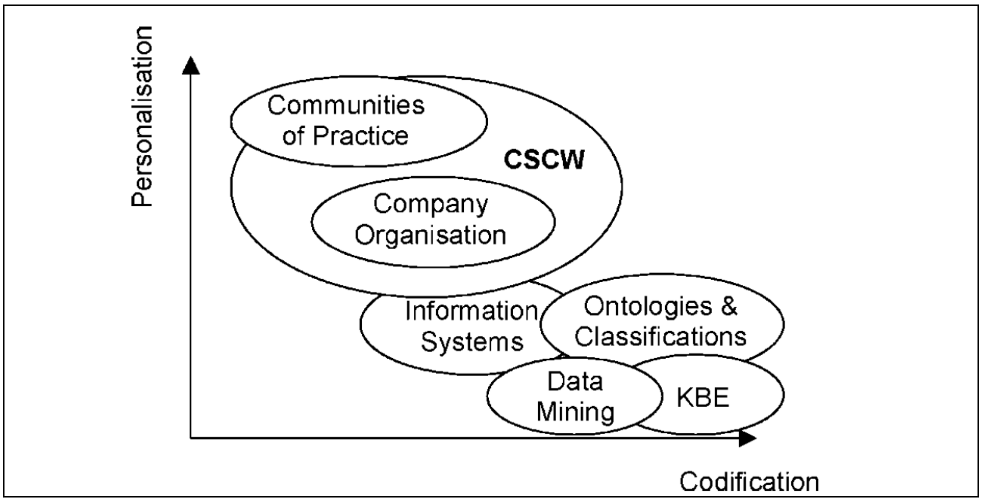


Figure 2.2: Perspectives on Knowledge Management (McMahon et al., 2004)

Wong and Radcliffe (Wong and Radcliffe, 2000) investigated tacit and explicit knowledge used in the design process of small hydraulic cylinders in an SME from a knowledge retention perspective, developing a knowledge schema to identify and segregate explicit and tacit knowledge (figure 2.3). The aim of the schema was to understand the relationship of various knowledge types in an engineering design context. It could be applied to any design situation and provided a framework to identify tacit components. Most of the knowledge identified in the design activities was explicit. The tacit element, know-x, was concerned with knowing what theory to use and knowing when to apply it. It can define rules such as if…then rules, but involves judgement which cannot be articulated. They suggest that this thought process can only currently be managed by people and cannot be automated. They concluded that the capture of 'know-x' is necessary to retain knowledge and design efficiency but paradoxically this cannot be achieved because it cannot be articulated.

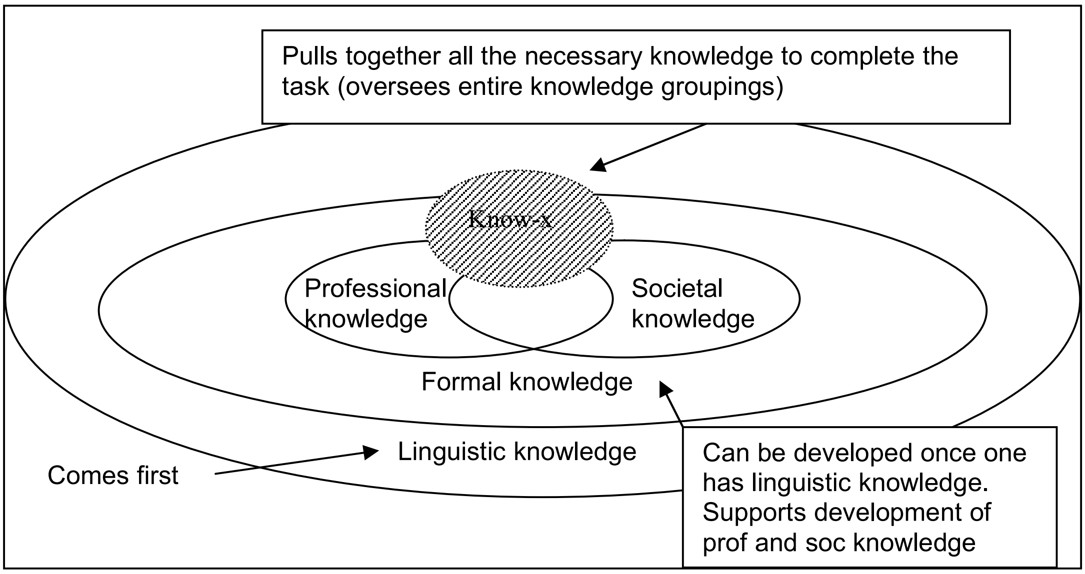


Figure 2.3: Wong and Radcliffe's knowledge schema (Wong and Radcliffe, 2000)

2.5.3 Key observations

In terms of content, manufacturing knowledge tends to be defined as method, capability and cost. The link between material, shape and process is strongly defined. There is recognition that such knowledge may be less detailed earlier in the design process, but this has not been defined specifically. Design knowledge and manufacturing knowledge have been noted as separated specialist domain areas with a need to share knowledge between them.

As with section 2.3, the themes of knowledge sharing and the need to support this within a knowledge management environment are apparent. Engineering knowledge is viewed as being, or needing to be explicit. However, the importance of support through tacit knowledge has also been acknowledged. The knowledge type and appropriate systems of support have also been linked to the nature of the engineering product and processes by McMahon et al.

Although new processes are acknowledged in both the Systematic Approach and DFMA (Pahl and Beitz, 1988; Boothroyd et al., 2002), the inherent nature of both methodologies is to select capable processes to reduce risk. Chen uses machining – a mature, stable and well-documented process – as a case study example for his system (Chen, 1999). Innovative manufacturing processes which are still in development and are therefore immature have not been considered. Bohn has discussed how processes are not inherently capable, particularly in high-tech industries. They require development work. Using processes at the lower stages of the table (4 and below) is labour-intensive and requires effort. It takes time to develop such processes to a capable standard (Bohn, 1994). This stance is echoed by Grant and Gregory in their study of the global transfer of manufacturing processes, noting that manufacturing processes will change over time according to their maturity (Grant and Gregory, 1997). Additionally, the tacit knowledge elements of these processes also require management.

The definitions of design process knowledge, particularly manufacturing knowledge, do fit with the definitions of knowledge management. The need to develop systems to deal with tacit and explicit knowledge is documented. However, there are two emerging gaps: the definition of manufacturing knowledge specifically for preliminary design and the consideration of innovative knowledge associated with manufacturing processes when designing knowledge management systems to support the engineering design process.

Section 2.5 highlighted the commodity and community approaches seen in knowledge management. The next sections will consider how these have been applied within the engineering design process, particularly for manufacturing knowledge.

2.6 Commodity Approach

The commodity approach is concerned with the capture, representation, use and re-use of knowledge, primarily within information systems. It is particularly applicable to situations where benefit is gained from re-use, particularly where there is some degree of standardisation in processes and / or knowledge use. In design it is particularly suited to variant design, although adaptive design can also be addressed using case-based reasoning systems.

Successful knowledge sharing is at the heart of the commodity approach. This is knowledge sharing from two perspectives. The main perspective is interoperability. In order for knowledge to be shared and successfully interpreted across different platforms, then it must be defined and represented in a standardised manner. From a technical point of view this requires the definition of knowledge exchange standards, protocols and languages, such as STEP, CORBA, UML and ontologies to define the knowledge requirements.

In this particular review the main interest in knowledge sharing is from a second perspective. This is concerned with the techniques used to define knowledge from a specific domain perspective and interpret this knowledge from the point of view of other domain perspectives. Two techniques which are of particular interest are features and information models, as both have been used extensively to represent design and manufacturing engineering. These two techniques, and systems using them, will be briefly reviewed.

2.6.1 Knowledge sharing using features

Features originated during the development of CAD/CAM systems as a means of conveying product data in a format which could be interpreted for manufacturing purposes. They were originally defined as attributes which sit above the pure geometry of a component to convey information which is of use in an engineering setting (Parry-Banuck and Bowyer, 1993) and early research into features investigated their use in the design and manufacturing domains, primarily focusing on the detail design stage of the product design process. As research progressed, the role of the feature expanded to other stages of the design process and other knowledge domains, such as assembly, concept design and tolerancing. Consequently the definition of a feature has also expanded to that of an information carrier to be used across the entire design process.

Two main techniques have been developed to exploit features: feature-recognition (also called feature extraction) and feature-based (also known as design-by-features). In feature recognition, manufacturing features are extracted from a model based on the geometry and topology. Research using this technique typically yields an automated NC / process plan generating system for manufacturing. With the feature-based approach, the product model is constructed from a number of pre-defined features enabling a product to be modelled relatively quickly. Pre-defined engineering information can also be conveyed within the features and be evident right from the start of the design phase. The aim is to embed process capability in the product during the design phase.

A third technique in features is feature conversion, also known as feature transformation or feature mapping. It is a features technique which is used to map features from one domain to another. This technique is used in multiple-feature view modelling, where a number of feature views relevant to particular domain activities can be created simultaneously. This technique is required to support multiple domain views for concurrent engineering.

In any system developed to use features, a clear, structured hierarchal definition – a taxonomy - is required, such as that presented in (Zha and Du, 2002) and (Gindy, 1989).

Information systems to support design and manufacturing analysis have been developed using the three feature technique methods, at varying stages of the design process and for a number of applications. Examples of the application of feature recognition to determine process capability are seen in (Naish et al., 1997) and (Dong and Vijayan, 1997) and both are concerned with machining processes. Examples of the use of a feature-based technique are seen in (Gao et al., 2000) for sheet metal work and in (Gayretli and Abdalla, 1999) and (Sharma and Gao, 2002) for machining. The latter is of particular interest because of the scope of the engineering design process in which it is used. Information systems using features have been mainly concerned with the detail design stage. With this example, there is a move into using features for a concept design system. However, as some initial geometry needs to be defined in order to use a feature-based technique, it does not follow the Pahl and Beitz definition of concept design. It may be better interpreted as an example of preliminary variant design for a re-use situation.

Brunetti and Golob's approach to adapting features to concept design was developed with reference to Pahl and Beitz (Brunetti and Golob, 2000). They concentrated on modelling the functional behaviour of a product using a working principle model so that it can be directly linked to the product geometry generated later in the design process. The authors proposed using a feature-based modelling of product semantics (especially in product function) approach to achieve this (Stork et al., 1996).

Bradley and Maropoulos also developed a product model using hybrid features to represent concept and embodiment for early design manufacturing analysis (Bradley and Maropoulos, 1995). The product model is tailored for embodiment stage by representing some overall dimensions but not detailed geometry. The main functions of the Concurrent Engineering Support System (CESS) developed are to generate a product specification, perform early manufacturability assessment during concept and embodiment and estimate costs. The system was demonstrated using a solenoid as a product example. Further work by Maropoulos widened the scope of manufacturing knowledge included. The CESS was supplemented by a rough-cut capacity planner for shop floor scheduling and a Computer Aided Process Planning (CAPP) system for detail design stage process planning, capacity and scheduling. The resulting system was called CAPABLE (Concurrent Assembly and Process Assessment Blocks for Engineering manufacture) (Maropoulos et al., 1998).

Examples of feature-based systems also developed to include more than one domain include Liang and O'Grady's feature-based distributed concurrent engineering (FBDCE) system to support the sharing and integration of design, engineering and manufacturing knowledge (Liang and O'Grady, 2002), Zhang and Xue's series of web-based databases for different stages of the product lifecycle using design and manufacturing features (Zhang and Xue, 2002) and Borg and Giannini's consideration of artefact features and life-cycle characteristics in addition to shape features (Borg and Giannini, 2003). They found that the quality of the evaluation was dependent on how much of the product it was possible to define.

A major limitation in the expansion of features has been the ability to model and view more than one feature view at a time. Feature conversion, and the resulting technique of multiple feature-view modelling (MFVM) can be used to create features at different stages of the product cycle and map them across. The method used to achieve conversion from one set of features to another is similar to feature recognition, however in this case one set of features is derived from another set of features (Bronsvoort and Jansen, 1993). The design view is accepted as the primary model view, with all model changes being driven through this view.

An example of such a system using MFVM can be seen in (De Martino et al., 1998). An intermediate model (IM) created by a design-by-features approach is the hub of the system and provides a shared product model providing different views of the product depending on the required application. The model is flexible and is able to view different independent self-contained subsets of the entire model depending on the application required. However, the feature transformation is one-way and if any updates are required, they need to be made via the primary model. De Kraker et al introduced the SPIFF system in 1995 as a means of addressing this issue (de Kraker et al., 1995). Their approach is to support all feature views simultaneously and to perform multiple feature conversions between these views.

The approach adopted could be said to work the opposite way to the typical feature conversion approach. The starting point for the system is the creation of a domain-specific view with a feature-based approach. This would probably be design but could equally be any other domain view. Any subsequent feature views can then be created by other domains using the original view as a basis – the geometry must be consistent. Updates carried out in one view can also be propagated across to other views. In this way, the system is designed to support dispersed collaboration in a concurrent engineering environment.

The use of feature semantics (the meaning attributed to a feature for a specific stage of the product lifecycle) has also been explored in the SPIFF system (Bidarra and Bronsvoort, 2000), presenting a semantic feature modelling approach as a solution. This object-oriented approach created feature classes as structured descriptions of all the properties of a given feature type (including validity conditions), known as semantics. It is user-interactive in that the users can define their own feature classes. The SPIFF system was developed further to become a web-based collaborative feature modelling system (WebSPIFF) which incorporates concept and assembly design, ensuring that a feature based model can be fully associative across the entire assembly rather than focussing on a single part. The developed system has the following functionality for collaborative design: concept design, assembly design, detail design and manufacturing planning (Bidarra et al., 2001; Bronsvoort and Noort, 2004).

Features have proved themselves to be useful in modelling stages in the design process. Their application has been primarily to products which are machined (although sheet metal work has also been demonstrated). There are however two limitations with features which are due to the way in which they are explicitly linked to component geometry. Although features are designed to show more than geometry, one must question whether they do fulfil that purpose given that they are formed from and linked to geometry. The second weakness is that in order to derive a feature it must already be based on some known geometry, therefore the design itself must have reached some stage of maturity in order for the feature to be derived. The success of their use in early design must therefore be questioned. Was it early design or showing a more mature product earlier? From a technical perspective, the number of feature views and their synchronisation would make an industrial application to a complex mechanical component prohibitive.

An alternative method of sharing knowledge which is not so tied to geometry, yet still offers some standardised knowledge sharing is sought. Such a method can be found in information models.

2.6.2 Knowledge sharing using information models

Information models are a formal method of standardising, structuring and representing knowledge. Developed to improve interoperability, they are usually modelled using standard languages such as UML. They are an attractive option for modelling knowledge in the design process because they are not as tied to geometry as features. Certainly geometric information is included and this can include features, but there is scope to include other wider sources of information.

The work by Young and a number of researchers define three types of information models for sharing design and manufacturing knowledge. These are the product model, the manufacturing model and the product range model. A product model contains all the information specific to the design of the product, with different views to represent each function. Consequently it has a manufacturing-specific view. A manufacturing model contains the information relating to the process capability and manufacturing resource availability (Lee and Young, 1998). Manufacturing information can be categorised into how to produce a part (product model) or how to use the manufacturing facilities in an enterprise (manufacturing model) (Young et al., 2000). A product range model provides a link between the product and manufacturing views, associating functional information with potential design solutions (Costa and Young, 2001). Information is shared between the different viewpoints of the different models using a knowledge transformation layer (Young et al., 2004).

The work has been primarily applied to support design for manufacture for injection moulding (Canciglieri and Young, 2003; Costa and Young, 2001; Lee and Young, 1998), although this work has also branched out into machining and assembly processes (Young et al., 2000) and consideration of global manufacturing facilities (Liu and Young, 2004). The work is primarily aimed at variant design, particularly for knowledge use – reuse situations, however Costa and Young also explored its application to adaptive design.

More recent work has been concerned with creating a shared meaning for design and manufacturing knowledge in an ontology (Young et al., 2007). The approach considered has been to use Process Specification Language (PSL) as the ontology language, as being mathematically based, it can provide a more rigorous definition when compared to text-based languages such as UML. The results have shown limitations but research is continuing to define a single foundation ontology. Keqin and Shurong have also recently created an ontology of manufacturing knowledge to support design decisions, working to the first four stages of Pahl and Beitz' approach. Here manufacturing knowledge has been modelled as relating to materials, machines and methods (Keqin and Shurong, 2008).

An example of an extended parametric information model can be seen in (Kleiner et al., 2003) in their development of a constraints-based approach to design and analysis. The principle was implemented in a system called Colibri (Constraint linking bridge) and applied to a mechatronics example, producing models for design in a CAD system, finite element analysis, multi-body system simulation and control design. The integration of data takes place via the properties shared by the constraints, meaning that the integration takes place within the geometry.

Information models are more flexible than features, however the information they contain must be codifiable to be expressed in a standardised language. Some attempts have been made by Young et al to classify knowledge as being explicit or tacit as a way of determining the best method for handling the knowledge (Young et al., 2004). Knowledge classified as explicit (i.e. tables, procedures and graphs) could be processed by information systems, tacit knowledge could not, except perhaps as a video clip. The examples of successful manufacturing models have also been created for mature manufacturing processes.

2.6.3 Examples of the commodity approach

Many examples of the commodity approach are collaborative systems for supporting a concurrent engineering environment. The focus of this research tends to be on solving interoperability problems and the integration of different platforms to support the engineering process. The platforms tend to be CADCAM, CAPP and PLM systems, sometimes with some KBE capability included. The most popular approach is to create a web-enabled system linking together either PLM and / or CAD systems using STEP for product data exchange and CORBA as a standard for object-oriented integration. A modelling language has also been used in the implementation – EXPRESS (modelling language created for STEP), Smalltalk, UML and XML have all featured. These systems may or may not use features and / or information models. One question is whether to have a large system with 'one size fits all' functionality (similar to the off-the-shelf ERP packages currently available) or whether to have a suite of product development tools which could be successfully integrated. This conundrum is discussed by Szykman et al with the latter approach being favoured for greater flexibility (Szykman et al., 2001).

Regarding interoperability, the challenge for the developers is '*to use the relevant model for each task (the right abstraction and granularity) and to communicate the results in a suitable form to the various parties involved, whose needs are different and interests are diverse'* (Wang and Zhang, 2002). Examples of collaborative systems to support concurrent engineering can be seen in (Chen and Liang, 2000; Chen et al., 1998; Gao et al., 2003; Gu and Chan, 1995; Jiang et al., 2002; Oh et al., 2001; Wolff et al., 2001 and Ye, 2002).

Early Design Support

Examples of collaborative systems developed to support the early stages of design can be seen in (Cera et al., 2002; Rodgers et al., 2001 and Haque et al., 2000).

Cera et al proposed a collaborative system to support knowledge based concept design using an integration of computer-aided design methods and a semantic web representation framework (Cera et al., 2002). Design semantics are defined as *'grounded representations of product and process knowledge.'* The system is designed to be used in situations where a design team is geographically dispersed. The semantics are intended as a method of communicating meaning which would normally be discussed in a co-located environment. They can also be used to represent information about the product in lieu of detailed geometry which can be added later, hence the suitability of the system for early stage design. Early stage design in this case is defined as a combination of two known approaches – functional modeling (as seen in mechanical engineering design) and freeform sketching (as seen in more consumer-based products). This system combines both approaches with *'controlled sketching…to capture the functional representation.'* Hence it is suited to less complex products where there is a functional and aesthetic consideration (perhaps consumer products), where a number of alternative solutions need to be created quickly for comparison to the design brief.

WebCADET is an internet-based knowledge server intended to support designers during concept design, however they do not define their interpretation of this (Rodgers et al., 2001). A case-based reasoning approach to decision making in concurrent engineering is also presented in (Haque et al., 2000). This approach is promoted as a means of strengthening early decisions. Some of the problems cited with end user needs include bias from memory recall, past product information may be dispersed or not available, the right person may not be available, lack of formal decision support, the iterative nature of design and lack of knowledge of the consequences of design decisions.

Consequently a knowledge-based support system is proposed for the early phases of NPD. A case –based reasoning approach was selected because of its ability to deal with multiple domains and the ability to carry out 'what-if' analyses. They used nearest neighbour algorithms to compare cases. One of the issues they found was in case similarity. The vocabulary may differ to describe same thing, despite standardised terminology and this may not be considered by the algorithm. *'the similarity percentage offered for each case in the results might not reflect the 'real' similarity of the cases, as* *understood by the user. The software does not show enough transparency and can affect the users' trust.'*

Complex Products

There are examples of design support systems and collaborative systems being developed to support early stage design for more complex products, primarily in the aerospace sector. Clarkson and Hamilton presented a parametric-driven task model of the design process called 'Signposting' (Clarkson and Hamilton, 2000). The aim of the tool was to support the iterative nature of the aircraft design process. The requirements for the system were that it should be relevant to all levels of skills and experience; able to capture, store and reuse data in a flexible manner within an iterative process; support multiple design tasks and guide the order of these tasks; have an integrated design environment; be useful and cost-effective. The model provides guidance on the next process to be followed rather than integrating the process itself. It has four tiers: the parameter level, which includes the parameters used to describe the design; the task level, which shows the tasks available to be used; the process level, which organises the tasks and finally, an interface level which enables users' access to the tasks. Guidance is achieved by scoring confidence in the maturity of a specific task.

Fujita and Kikuchi's research is concerned with the concurrent support of preliminary aircraft design (Fujita and Kikuchi, 2003). Their definition of preliminary design is more precise than many of the examples discussed in this section. It is seen as the stage between concept design and detail design, where the main dimensions which size the product (in this case, an aircraft) are set to meet the performance criteria. The sub-systems are then considered in increasing detail. This definition is comparative to the process described by Pahl and Beitz. Three concepts within the design process are considered: the management of trade-offs between different disciplines to give a compromise solution (called 'satisficing'); the ability of the product to be decomposed into a number of subsystems to focus design efforts and the increasing detail (granularity) in the design as it moves from preliminary to detail stages. Consequently an abstraction of a large complicated design problem is required to develop a general system of solution. They propose a distributed design support system which is develop in a CAD system, using knowledge-based techniques and agent-based distribution of tasks.

Savci and Kayis took a risk management approach to concurrent engineering, developing the IRMAS (Intelligent Risk Mapping and Assessment System) to consider the cumulative risks generated by the interdependency of tasks (Savci and Kayis, 2006). The system was trialled in the aerospace industry, looking specifically at advanced composite manufacture and aerospace design. Of particular concern were risks encountered during preliminary design, defined as *'incomplete preliminary manufacturing engineering validation, tooling design, and customer requirements analysis.'*

Manufacturability Assessment

Other researchers have used the commodity approach to develop systems which specifically consider the manufacturability of a product. Lovatt and Shercliff extended their earlier work on process selection into a task-based methodology (Lovatt and Shercliff, 1998b). However, the preliminary design stage is fixed prior to the use of the methodology. The requirement for the task-based selection is to determine viable material / process combinations in terms of technical feasibility and cost effectiveness. Therefore design and material 'performance' and 'processability' (process capability and cost) were considered. The starting point is a matrix of all possible process / material combinations. Each stage is then used to screen out the non-feasible options. As the material and process selection becomes more refined at each stage, more detail can then be introduced. At the initial screening, all the obviously unfeasible combinations are eliminated. During a primary assessment, the possible combinations are compared with technical process feasibility and screened on these requirements. Then during a performance assessment the 'processability' of the filtered combinations is examined together with performance and cost criteria. Finally an economic evaluation takes place. A scheme of the methodology is shown in the figure 2.4 (reproduced). The detail of each phase is summarised in table 2.4. Qualitative process comments are included during the preliminary and performance assessment. The methodology was built into a software package and was demonstrated in carbon steel cutting, aluminium casting and carbon steel welding, although the details of this were out of scope of the paper.

Zha considered the selection of materials and manufacturing processes in a concurrent DFM environment (Zha, 2005). The focus again was on the early stage of design, although again this was not defined. Design requirements were categorised as material properties, form requirements and production requirements (lead-time, rate and quantity). They claimed that these categories could also be used for the categorisation of process requirements. The rationale for process selection was cost-based with a systematic solution of suitable materials and processes. Process capability and material property data were used to carry out assessments using a fuzzy knowledge-based approach.

Bordegoni and Cugini developed a design support system to capture process and rationale (Bordegoni and Cugini, 2002). It is designed to support the capture and representation of design and manufacturing knowledge for re-use. The rule-based system is based on a multi-level knowledge model for design and manufacturing knowledge management incorporating the product structure, starting with the physical principle level (which contained general design rules), the architecture level (parametric modelling of constraints imposed by the physical principles), solution families (division of architecture into sub-systems) and instances (specific projects). The design and manufacturing constraints capture rules and parameters mainly related to the selected shape and material of the component.

A knowledge management database was developed to support the manufacturing assessment of gas turbine engines (Balogun et al., 2004). The database used a feature-

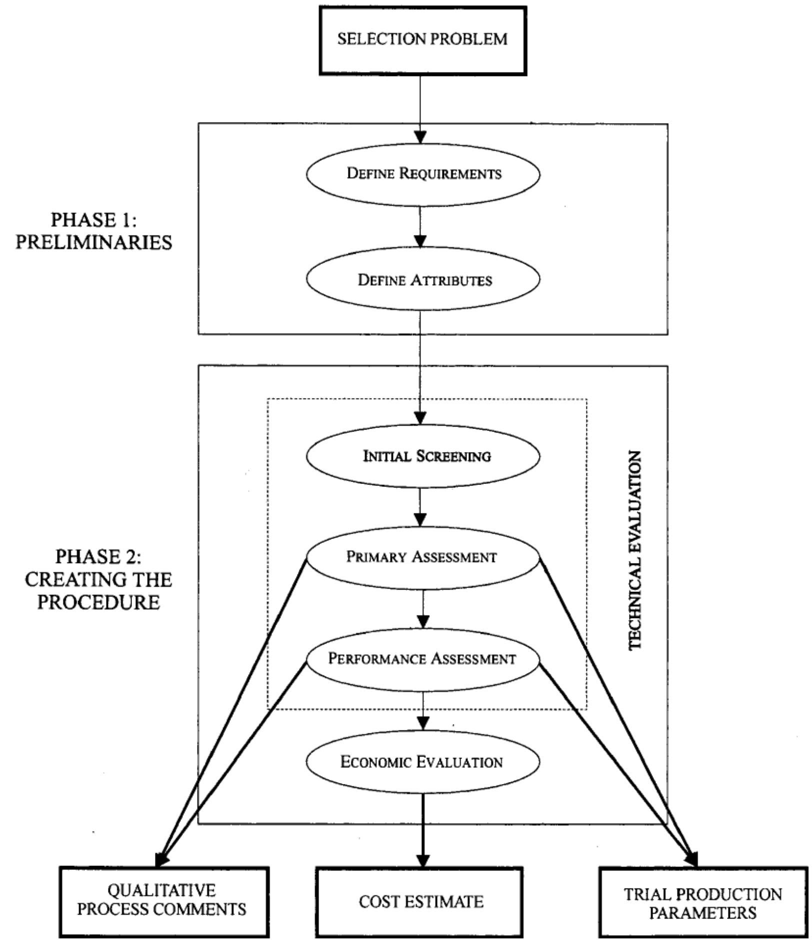


Fig. 1. General scheme of the methodology.

Figure 2.4: Lovatt and Shercliff's Methodology (Lovatt and Shercliff, 1998b)

based product model and an integrated process model. Specific operations from the process model linked into the product model at component and feature levels. The database functionality includes assessment of manufacturing processes, costs and capability (where capability is defined as ability to meet tolerance and is linked to Cp and Cpk values from a general database or from inspection data). A risk assessment is also carried out on the process based on costs from scrap and rework. Material data is also included and linked to the manufacturing processes and components.

Van der Laan and van Tooren proposed a method for automating the management of trade-offs during the early stage of design for aerospace components, particularly aimed at manufacturing analysis and costing (van der Laan and van Tooren, 2005). Their argument was that other technical analyses (such as aerodynamics and stress) could be performed at this early stage and therefore this could be expanded to manufacturing.

Table 2.4: Steps in Lovatt and Shercliff's Methodology (Lovatt and Shercliff, 1998b)

Phase 1: Preliminaries
Step 1: describe m/f task in detail, inc.:- - relevant material / process combinations; - Extent of material co-selection; - Scope of design and m/f issues; - Level of detail rqd. Step 2: describing a process: the attributes Atttibutes: 'parameters which describe a process and its capabilities' Attributes: material-related, design-related, manufacturing-related. Attributes can be single values and rankings (qualitative data), ranges or functions depending on nature of data available and level of detail required.
Phase 2: Create the selection procedure
Step 1: Initial screening ('perform attribute-based selection using range-type attributes.') Step 2: Preliminary assessment – can the component be produced by the process? Requirements are mainly 'component geometry related'. Step 3: Performance assessment – can component performance be achieved? (Examine relationship between combinations, performance requirements and processibility). Step 4: Economic evaluation – not a full-scale costing calculation, but combinations are screened based on economic viability. Cost elements considered are investment (one-off set up costs), operational (daily costs) and overheads.

The stage they considered very much fits in with the preliminary stage according to Pahl and Beitz. The data was generated in a 'Design and Engineering Engine' (DEE) with a product model as the main input. Parameters were used for each design and to define the manufacturing process. A specific manufacturing model view was also created with the aim of removing unfeasible manufacturing concepts at an early stage. Some degree of cost estimation also took place using historical data. A composite lay-up was demonstrated.

The Intelligent Master Model project is a GE project which investigated the development of an integrated multidisciplinary design and analysis system by integrating CAD and CAE tools (Cedar, 2004). The system is designed to support GE's philosophy of robust design (using Six Sigma) to meet product and process capability. The product considered is aviation gas turbine engines.

The main concept which drives the integrated system is the Intelligent Master Model (IMM). This enables parametric design to take place against built-in design rules and best practices to meet the product specifications. It was implemented using scaled parametrics from an existing engine, indicating the element of 're-use' in design There are three components to the IMM: the Master Model, which uses a feature-based parametric approach and facilitates the creation of context models for analysis; the Product Component Structure (PCS) which gives a 'top down' high-level assembly view of the product and enables component geometric changes to be associative throughout the whole assembly and the Product Assembly (PA), which is a 'bottom up' detailed view of the components within the assembly. Updates within this structure are associative throughout the product due to the link with the PCS and the Context Model Architecture (CMA), which is an intermediate model created from a copy of the master model which can be viewed as different context-specific models for different analysis activities. There is also an additional Link Model Environment (LME) which is an integration environment. The modelling was implemented during the later stages of preliminary design and detailed design. Originally, the aim was to introduce it during earlier stages of preliminary design but it did not have sufficient flexibility. Two pilots were reported: the construction and analysis of a 3D solid geometry model for a compressor assembly (Bailey, and VerDuin, 2000). Two models were demonstrated – a heat transfer model and a manufacturing model. The latter was used in conjunction with a 3D master model to generate process plans, tooling and CNC data and a CMM model. The second pilot was focussed on the creation and validation of four context models for analysis – a 3D conjugate heat transfer module (combines aerodynamic, combustion, heat transfer and mechanical analyses in one model), a 2D mechanical model, a 3D stress model and a 2D sub-system dynamics model (Seeley et al., 2001).

Recent Examples

Two more recent examples of research have implemented mathematically modelled methodologies as object-oriented solutions. Xiao et al developed the Collaborative Multidisciplinary Decision-making Methodology (CMDM) to enable *'collaboration by separation'* (Xiao et al., 2007). Here, design and manufacturing teams work independently to solve their relevant problems associated with the design of a new product. The CMDM seeks to reduce the amount of iteration between the two areas by acting as a decision support system which reduces the degrees of freedom available for the solution at each stage, thus eliminating unsuitable design solutions early in the process. There are three elements to the CMDM: a compromise Decision Support Program which is a mathematical model represented by a XML object-oriented data model, to enable information to be transferred without iteration, game theory to model the most effective interactions between design and manufacturing and design capability indices to specify target design values.

Du et al also presented an example using stream of variation (SoV) methodology during product design to make early predictions of product quality (Du et al., 2008). This methodology was a framework with three elements: multivariable statistics, control theory and design and manufacturing knowledge. The methodology was designed to evaluate the product design and process variables and in doing so predict any manufacturing problems which may occur later in the later stages of the design process. The stages of design and manufacture considered are not defined, but appear to be based on detail design, with modelling of the product features and geometry and process operation details and sequences.

2.6.4 Key Observations

The commodity approach has been very successful in developing structured and standardised examples of knowledge representation. The strength of the approach and hence focus of research is the ability to automate and therefore improve the efficiency of routine design process tasks and analyses. For this to be successful, the systems need to deal with 'known' knowledge - the design product considered is usually variant, its parameters are known and the manufacturing process is mature. Conversely, knowledge which is immature, has some degree of being 'unknown' and comes from people is seen as undefined, incomplete and unreliable. The automated approach is seen as being more technically rigorous and therefore preferable.

The issue of interoperability is well recognised and is a prime focus of research activity. Therefore the emphasis tends to be on the technical issues rather than the definition of the knowledge itself. Consequently many systems are demonstrated using simplistic examples which cannot reflect the design issues associated with complex mechanical components. Also, although many systems are aimed at 'concept' or 'early stage' design there is no real definition of this in terms of design process and knowledge requirements. There are some examples applied specifically to complex mechanical components, however. These have been important in defining how knowledge is required to manage the trade-off for requirements from multiple engineering disciplines.

2.7 Community Approach

2.7.1 Criticism of the Commodity Approach

The business management sector of research has been critical of the 'commodity' approach to knowledge management. Walsham maintains that information systems do not improve communication between people (Walsham, 2001). There are two reasons for this. The first is because the explicit and tacit elements of the knowledge are divorced. Walsham suggests that the commodity approach misunderstands and misrepresents tacit knowledge. It is seen as something which can be converted into explicit knowledge and then stored, i.e. as a transferable object, contrary to Polanyi's original definition. Consequently, explicit knowledge has been promoted at the expense of instilling meaning from tacit knowledge and such systems have ignored the need to manage knowledge simultaneously at both the explicit and tacit levels. The second reason is concerned with the sense-reading and sense-giving aspects of tacit knowledge transfer, again referring to Polanyi's original definition. An example of this is illustrated by the writing of a letter about new experiences. *'this is not a simple process of "knowledge transfer" as depicted by the "knowledge as a commodity" literature. The sense-reading of person A is not perfectly depicted in the attempt at sense-giving in the letter, and is certainly not the* *same as the sense-reading which is then carried out by person B.'* Thus Walsham is illustrating the importance of the tacit element of knowledge in sharing knowledge across different domains.

Walsham does not reject the use of ICTs in knowledge management, recognising that they do serve an important purpose. He suggests that instead knowledge systems should be designed to promote the value of the sense reading and sense giving activities – this will give them value. Two methods are suggested – communities of practice within a shared boundary and organisational translators across domain boundaries.

Roberts also examines the issue of knowledge transfer through the use of ICTs and issues surrounding explicit and tacit knowledge transfer (Roberts, 2000). She shares the same knowledge definitions and perspectives as Walsham, again citing Polanyi and Nonaka's definitions of tacit and explicit knowledge. Knowledge transfer is defined as the diffusion of knowledge from an individual to others. The knowledge transfer process is achieved by socialisation, education and learning which can either occur deliberately or as a by-product of another activity. She notes that person-to-person (and preferably face-to-face) communication is the most critical element of technology transfer.

Roberts also raises the issue of trust in knowledge transfer, stating that this is important in the exchange of tacit knowledge and that this can be achieved by initial social contact, particularly across different social backgrounds. She concludes that this can only be initiated from face-to-face contact and is something that is not acknowledged in ICT system development. She suggests that even video conferencing is insufficient for tacit knowledge transfer and trust building as the process of digitisation codifies the human element of the contact. Furthermore, initial tacit knowledge transfer is an essential pre-requisite for explicit knowledge transfer.

Johannessen et al, noting that increasing investment in IT does not appear to have reaped the benefits, were also concerned about the focus on explicit knowledge being to the detriment of tacit knowledge transfer (Johannessen et al., 2001). Like Walsham and Roberts, the focus of their research was to improve understanding of tacit knowledge and give guidance on how to handle the relationship between tacit knowledge and IT. They were specifically concerned with the influence of tacit knowledge on the use of IT systems and vice versa. They saw the organisational challenge as being to transform personal tacit knowledge into organisational explicit knowledge. Processes for building trust and relationships are seen as being pivotal to this, illustrated by their case study at a Norwegian shipyard.

The company was organised into teams based on an instructor-apprentice model which enabled job rotation to take place so everybody had at least a basic appreciation of each other's jobs. Consequently they became more inclined to share knowledge. This led to some teams proposing changes to the design philosophy which would improve efficiency within the process. The top management structure was disinclined to implement this, as they had proposed the original philosophy, however the changes were eventually implemented after a process change procedure was instigated. This work highlighted two implications of enabling tacit knowledge transfer: the first is that it can have consequences for the organisational structure and philosophies of an organisation and secondly, that not everybody is always willing to acknowledge or permit the consequences of tacit knowledge transfer.

They too see the exchange of tacit and explicit knowledge as being necessary for innovation, arguing that tacit knowledge by itself will only lead to continuous improvement at the most because it can be conservative and subject to internal barriers. Their conclusions are similar to those seen in Nonaka's SECI model, however little evidence is offered in this particular research work to support the claim.

Swan et al also acknowledge the benefits of IT for knowledge re-use situations, but note that IT-based knowledge management projects which focus primarily on codifying knowledge will not be able to deal with innovative knowledge (Swan et al., 1999). They view innovation as a time-phased multi-function communication process within an organisation, therefore knowledge sharing is essential for this process and the development of new innovative approaches. They also share the stance that tacit knowledge cannot be codified because of its personal and context-specific elements. It may be too uncertain; it may be too context dependent and therefore irrelevant; it may be too politically sensitive and it may be inaccurate. Consequently networking, a social communication process, is promoted as a major requirement of a successful process-based approach to innovation. The main challenge in achieving this is successful communication across different organisational boundaries and the development of organisational mechanisms to achieve this. They argue that a '*common stock of knowledge'* needs to be built to facilitate this, hence this is no longer a straightforward knowledge transfer process. Therefore the traditional knowledge management / commodity (called cognitive) approach no longer applies. Furthermore, the development of systems for the capture and re-use of explicit knowledge (IT-based) may inhibit the development and benefits of social networks. There needs to be more development of communities of practice and social networking to promote interactive approaches for innovation alongside the IT emphasis. However, they do acknowledge that developing tacit knowledge networks can take time and be difficult in an organisation with geographically-dispersed sites.

Addressing these criticisms

Some researchers whose prime focus is the commodity approach have more recently attempted to recognise and address tacit knowledge requirements. Some examples include those considered by Perez-Araos et al, Cheung et al and Koh and Gunasekaran.

Perez-Arao et al acknowledge that IT-based systems have managed explicit knowledge at the expense of tacit knowledge (Perez-Araos et al., 2007). However, their response is that tacit methods are not particularly prescriptive and therefore useful in fully harnessing this approach. They acknowledge Nonaka's theory of knowledge creation but their interpretation of tacit knowledge appears to be flawed, as they demonstrate the misconception that tacit knowledge can be converted into explicit knowledge. Bolisano and Scarso also attempted to map knowledge captured to Nonaka's SECI model (Bolisano and Scarso, 1999). They carried out four case studies, each of which mapped to one of the mechanisms in the model. The examples used were electronic data exchange (explicit – explicit transfer), a CD-ROM spare parts catalogue (explicit – tacit transfer), CADCAM (tacit – explicit) and design databanks (of graphical images) for shoe design (tacit – tacit transfer). Some of these selections do not agree with some of the examples seen elsewhere in this review. The CADCAM example could be construed as explicit – explicit as tacit knowledge is lost in codification. This was demonstrated in (Siu and Dilnot, 2001). Similarly, it is argued that the design databanks of graphics for shoe design are also examples of codified and therefore explicit knowledge. The authors again propose that tacit knowledge can be converted into explicit knowledge. Their examples demonstrate that this is not a straightforward conversion. They appear to miss the subtleties in their examples of knowledge transfer and understanding of the definition of knowledge.

Cheung et al acknowledge the necessity of tacit knowledge for knowledge sharing and seek to codify employee tacit knowledge and experience as part of 'know-how' in their latest development of an internet-based PDM system for collaborative product development (Cheung et al., 2006). Although not directly relevant to the research being reviewed in this chapter, Koh and Gunasekaran's work on managing uncertainty in manufacturing operations planning and scheduling is another demonstration of attempts to convert tacit knowledge into explicit knowledge (Koh and Gunasekaran, 2006). A hypothesis of human factors considerations in the development of a collaborative system was presented in (Harvey and Koubek, 2000). Although tacit and explicit knowledge were not specifically discussed, the work is more in keeping with the accepted definitions.

The papers in this section have contributed some interesting definitions and discussions on the appropriate uses, strengths and weaknesses of explicit and tacit knowledge. The importance of tacit knowledge has been shown in particular to be strong for two purposes: for sharing knowledge between across different specialist domains and for sharing innovative knowledge. Many of the cases included here have been investigative and explanatory. The importance of tacit knowledge has been documented, but not the means to achieve it. The next section discusses methods by which the community approach has been applied to sharing knowledge and particularly design and manufacturing engineering knowledge.

2.7.2 Examples of the Community Approach

Bresnen investigated enablers and barriers to knowledge transfer in a process-change project to improve knowledge management (Bresnen et al., 2003). The aim of the research was to investigate social practices to find effective community approaches to sharing tacit knowledge. The focus of the research was the introduction of a new management job role to facilitate knowledge sharing and best practices in engineering across the company.

The modes of networking and communication for the job role were reported as networks of personal contacts, email, but with face-to-face and word of mouth dominating. Six enablers and barriers to knowledge capture and diffusion were identified which were mainly concerned with social processes and organisational factors: the effects of organisational structure; cultural context; the manager's own skills and capabilities; communication, networks and information flows; technology mechanisms and the rigidity of objectives. As the knowledge transfer activities took place within the same discipline (engineering) then there was no examination of cross-functional boundaries.

Cross-functional boundaries

In a review of teamworking and knowledge management, Sapsed et al focused on the benefits of using cross-functional teams for exchanging knowledge across organisational boundaries (Sapsed et al., 2002). An example of creative benefits in this style of working was in new product introduction. The benefits of such teams are in knowledge integration rather than the teams themselves.

Dougherty offered some explanations as to why problems are found with knowledge sharing across different organisational boundaries, particularly concerning innovation in large firms (Dougherty, 1992). The focus of her research was the investigation of barriers which may hinder the success of new product introduction. From carrying out a multiple case study of eighteen new products in five firms, she proposes two reasons why this may be the case: different 'thought worlds' and 'organisational routines'.

She uses the term 'thought worlds' from research by Fleck (1979) and defines the term as *'a community of persons engaged in a certain domain of activity who have a shared understanding about that activity'*. It is necessary within the innovation process to be able to combine the perspectives of several 'thought worlds'. Collectively the different thought worlds identified in her case study research had the same organisation goal. However within each 'thought world' she identified not only different shared common knowledge but different ways of processing the knowledge, which she called knowledge systems. A summary of the results is reproduced in table 2.5. She concludes that it is necessary for management to understand the importance of collective perspectives as they transcend what may be perceived as goal or political conflicts.

Table 2.5: Differences in the Thought World Systems of Meaning about Product Innovation (Dougherty, 1992)

Themes that differentiate thought worlds	The technical people	The field people	The manufacturing people	The planning people
What is seen when looking into future / uncertainties	Future comprises emergence of the technologies underlying the new product: design problems and their solution, new technical possibilities to include, new trends which might change development. Uncertainties comprise finding out what the design parameters are.	Future comprises shifts or trends in the users' uses of and need for this and related products. Uncertainties compromise how to get to buyers, discern if they like product, and how to adjust product for user.	Future limited to capabilities in plant, need careful shifts in operations. Uncertainties concern if manufacture is possible, what are the volumes.	Future comprises emerging business opportunities, competitive changes, new niches. Uncertainties concern developing market forecasts and income projections.
Aspects of development considered most critical	Focus on devising the product, specifying what it should do. Want to know what users want in product specifications. Market is seen as what the product does, and as such is rather obvious.	Focus on matching products to users, adjusting the product quickly to meet their shifting needs, creating the sale. Want to know who makes buying decision, what problems customers want to solve. Market is seen as what the buyer wants, and as such is difficult to develop.	Focus on the product's durability, quality, how many types of product. Want to know how good is good enough in product quality. The market is seen in abstract terms as product's performance.	Focus on developing the business case and general marketing plans. Want to know the best segment to be in, how to position the product in this segment. Market is seen as a general business opportunity.
How development task is understood	Task is to build the product – a hands-on, tactile activity. Product is real, has a physical presence and is 'neat'.	Task is to develop relationships with buyers, which occurs when products change to meet their needs. Sense of task is one of urgency. Also hands-on but product is not real – it is a possibility.	Task is to build the capacity to build the product. Also hands-on, tactile, product is well built.	Task is to analyze alternative possibilities, determine income potential – a conceptual, abstract activity. Product is a business

After identifying the thought worlds, the research then considered organisational routines, their effect on product innovation and their effect on collective 'thought world' activities. Three routines were identified: interdepartmental relations, market definitions and product standards. All three were capable of hindering the innovation process. Strictly defined roles (interdepartmental relations) could hinder mutual learning, market definitions would constrain the impact of technology on new products and therefore discourage the use of new innovative ideas and product standards could impose existing standards on new products which were incompatible. The organisations which were able to break away from or subvert these routines were shown to have the most success in innovation and new product introduction.

Huang and Newell investigated the phenomena of cross-functional teams further (Huang and Newell, 2003). Their research concentrated on identifying and understanding the mechanisms within cross-functional teams which led to successful knowledge sharing and integration. This took place in four companies, investigating a project from each. The projects studied were the development of software for product innovation in an investment bank; the implementation of an ERP system in an engineering company; the introduction of Business Process Re-engineering in a retail company and the implementation of a Knowledge Management process in a petrochemicals company. The data was collected from observations, semi-structured interviews, information dialogue and documentation and a qualitative code developed to analyse the results. A model of knowledge integration in the context of cross-functional teams was developed from the code which covered the scope, efficiency and flexibility of integration. The components contributing to these were project awareness, common knowledge, embedded practice, past integration experience and social capital.

Fernie et al investigated sharing context by exploring knowledge sharing of best practice between the aerospace and construction industries (Fernie et al., 2003). They focused on tacit knowledge with no attempt at codifying knowledge. Socialisation was seen as being key to the sharing of tacit knowledge. For this particular case, some degree of debate and controversy was also necessary for successful knowledge sharing. They suggest that tacit knowledge is paradigm-dependent which can make it difficult to generalise or apply to other contexts. Much of this is influenced by the factors which influence context in cross-industrial sector knowledge sharing. These factors can be political, economic, social, technological, legal, environmental and structural. Much content is also historical.

They found that knowledge could not be separated from its context. For the subject considered (supply chain management), there were some considerable differences between the two sectors in terms of numbers of the number of companies in the supply chain, the way in which they competed and the way in which they functioned in the two industries. This made it difficult to identify knowledge applicable to both sectors. In fact, it made the researchers and participants question the assumption that knowledge can be shared and be applicable across different sectors. It was also concluded that the approach had been an alternative socialisation technique which challenged that approach of codifying knowledge.

The main method by which the community approach has been adopted in design and manufacturing engineering has been through the use of cross-functional teams. Such teams are an important part of the CE philosophy, called multi-disciplinary teams, tiger teams, process action teams and integrated product development teams (Pawar and Sharifi, 1997). However, it is important to note that much of the literature on such teams pre-dates the ascendance of knowledge management as a research discipline (and the community and commodity approaches) or has not been subjected to a knowledge management analysis. There appears to be a general consensus that these teams have been effective (for examples see Medhat and Rook, 1997; Deitz, 1995; Laufer et al., 1996), but very little literature could be found on investigations into how and why this should be the case.

A typical example of the literature is seen in (Deitz, 1995), which reports on the organisation of departments in a CE environment for Westinghouse gas turbine engines. Their multi-disciplinary design teams are cited as one of the main reasons for success with CE (the other being integrated computer support), because they enable a continuous process of product development and immediate feedback. Smith takes a historical view of CE, claiming that the main tenets of the philosophy have been recognised as engineering best practice since the early 20th century and that CE is the integration of all of these rather than a purely new practice (Smith, 1997). Again, cross-functional teams are recognised as probably the most effective method of achieving integration.

Potential obstacles to achieving teamwork in CE are discussed in (Nicholas, 1994). One such problem cited is the differing attitudes, goals and viewpoints between members from different functions (echoing Dougherty's 'thought worlds'). These can be overcome with effective organisation, leadership and instilled behaviours. Pawar and Sharifi compared virtual and co-located teams, arguing that for the latter case, intra-team communication becomes a major factor in the performance of the team due to their different domain interpretations (Pawar and Sharifi, 1997). The study found that the co-located team were able to communicate more effectively between themselves but found it more difficult to access information and to interact outside their group. The virtual group found the lack of immediate contact for discussing ideas and issues frustrating and ultimately demotivating.

Hauptmann and Hirji reported on a large global study of cross-functional teams in CE (Hauptmann and Hirji, 1996). The aims were to ascertain the processes and behaviours which influence concurrency and how these contribute to the outcome of the projects. The four processes / behaviours identified were '*two-way communication; overlapping problem solving'* and being able to use and release *'incomplete and uncertain information'*. These contributed to *'team satisfaction, project cost and schedule and product cost and quality.'*

Cross-functional teams and innovation

More recently Love and Roper carried out research to investigate the importance of cross-functional teams and innovation (Love and Roper, 2009). Of particular interest was the issue of complimentarity, which considered the codification and transfer of knowledge between domains but also *'whether knowledge created at one stage can be properly understood at the next stage without the presences of specialists similar to those in the preceding stage.'* They found that the strongest contribution to innovation from cross-functional teams tended to be in the technical and engineering areas (including manufacturing). The reasons for this were not explored however the researcher speculated on possible reasons for this, remarking that it may be due to similarities in organisational structure and approaches to knowledge codification.

Carlile identified three barriers to integrating knowledge during NPD (Carlile, 2002). These were the syntactic and semantic boundaries (from existing research) and the pragmatic boundary (proposed in the research). The syntactic boundary refers to the shared context and language which makes codification possible. In order for knowledge to be transferred then the syntax must be common. Carlile proposes that novelty in knowledge will have a syntactic boundary because it will not be comprehended by the current syntax. The second barrier is the semantic boundary, referring to the way in which different meanings can be applied to the same knowledge due to different unshared contexts. Carlile notes that this is possible even with a common syntax. The pragmatic boundary *'assumes the conditions of difference, dependence and novelty are all present, and so recognises the requirement of an overall process for transforming existing knowledge to deal with negative consequences that arise.'* With the pragmatic approach, knowledge is described as being localised (pertaining to a specific problem which needs solving); embedded (from experience and 'know-how') and invested in practice (the value of the developed knowledge is in its ability to solve problems successfully). All of these dimensions are useful in communities of practice, but can cause problems in transfer across boundaries.

Boundary objects are proposed as a means of spanning the knowledge barrier. These have a shared syntax, can clearly differentiate semantic meanings and facilitate a process for knowledge transformation which will account for novelty. Examples of boundary objects are repositories, standard forms and methods (such as DFMA), objects and models (such as a CAD model) and maps to show systematic dependencies between groups.

A knowledge transformation cycle was proposed for sharing new knowledge across boundaries (Carlile and Rebentisch, 2003). There are three stages to the cycle developed. The first stage is storage, because this refers to knowledge currently existing in a 'steady state' in the organisation. This can be either documented knowledge or the collective organisational 'tacit' knowledge. The next stage is retrieval. In order for new knowledge to be subsumed, it must be compared to existing knowledge and the use of the knowledge. Finally the transformation stage refers to the use of the knowledge to create solutions to problems across and within specialist domains. In doing so some novelty – and new knowledge – is created. However a main barrier to the transformation across boundaries in their case studies was the lack of a shared syntax. Boundary objects were seen as a potential solution to this.

The findings from the two papers discussed were consolidated into an *'integrative framework for managing knowledge across boundaries'* for innovation (Carlile, 2004). The framework, seen in figure 2.5 (reproduced) is demonstrated using an example of new product development in the automotive industry.

Where there is a joint syntax across the boundary, knowledge integration is possible. As novelty increases, other boundaries gain importance. The semantic boundary is useful in creating a shared meaning, using activities such as cross-functional teams and activities. However, Carlile makes the point that when there are different contexts *'creating common meaning is not possible; what is required is a process in which actors negotiate and are willing to change the knowledge and interests from their own domain.'* The pragmatic boundary occurs when the presence of novelty results in different interests. Hence the shared meaning needs to be renegotiated and boundary objects must be able to represent 'trade-offs'. This framework is not intended to be a mathematical model because only the syntactic boundary can be expressed in this way.

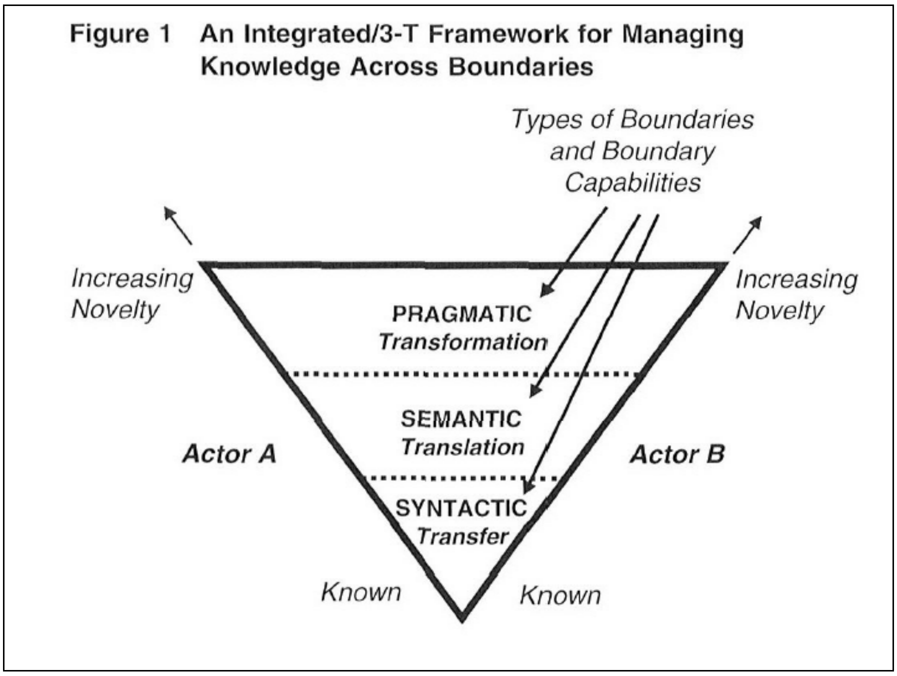


Figure 2.5: Carlile's Framework for Managing Knowledge Across Boundaries
(Carlile, 2004)

An empirical case was then presented to illustrate the framework (not as a means of validation). It dealt with the early automotive development. This involves the early definition of constraints on the product which are vehicle styling, engine / power train, climate control and safety. The study explored the results of implementing a recently developed simulation tool. The most challenging part of the development was found to be relating the consequences of changes in one engineering domain on other engineering domains. Problems arose when a novelty in the design was wrongly interpreted during simulation. The authors interpret the findings as the ability of the tool to manage the syntactic and semantic boundaries, but not the pragmatic boundary.

2.7.3 Key Observations

As advocated in (McMahon et al., 2004), engineering in the design process needs to consider tacit and explicit knowledge. This section has expanded on this claim to illustrate why the inclusion of tacit knowledge is important and some methods which may be used to achieve this. The tacit element has been shown to be important for both sharing knowledge, particularly between different domains and particularly in sharing innovative knowledge. The methods to achieve this are primarily of a social nature and include networking and cross-functional teams. Tacit knowledge is valuable because it deals with trust, shared context and makes sense of the different 'thought worlds' encountered in a knowledge sharing environment. However, it is important to note that these can also be active barriers to successful knowledge sharing. The Concurrent Engineering approach has advocated the use of cross-functional teams for effective knowledge sharing prior to any analysis of explicit and tacit knowledge.

Those who support the community approach do not do so at the expense of the commodity approach, recognising that a combination of both is required for the effective sharing of innovative knowledge. There is evidence too that those who work in the commodity field are also beginning to consider tacit knowledge, although there have been misrepresentations of tacit knowledge. The next section discusses potential methods by which a combined approach could be achieved.

2.8 Towards a Combined Commodity and Community Approach

There does not seem to be much literature published in this area. This section discusses four relevant contributions that were found. The first is concerned with a sociotechnical approach to aerospace design. The second is the use of an ontology. The final two are methods to be used in business which have more structured approaches to capturing and structuring strategic knowledge gaps using explicit and tacit knowledge methods.

2.8.1 Sociotechnology

The sociotechnology approach has been promoted as a potential solution to deal with the need to span the community and commodity approaches. Sociotechnical theory is defined as follows: *'(it) has at its core the notion that the design and performance of new systems can be improved, and indeed can only work satisfactorily if the 'social' and 'technical' are brought together and treated as interdependent aspects of a work system'*(Clegg et al., 2000).

The sociotechnical approach has been applied to system design (Waterson et al., 2002) and design of work systems (Clegg, 2000). An application of particular relevance to this project is knowledge management in aerospace design (Kerr et al., 2001).

The research used a socio-technical approach to study knowledge management in design from a multi-disciplinary perspective. The objective was to understand the *'human, social, organisational and technological aspects of current knowledge capture, sharing and reuse activities.*' The rationale for the research is that design can be viewed as a *'sociotechnical enterprise'* because it incorporates teams, technology and the individual. A particular motivation was the knowledge management challenges in engineering design, particularly whether knowledge can be re-used in an environment which is often uncertain.

The research took place in two major UK aerospace companies. Twelve in-depth interviews were conducted in both companies. Each interviewee talked through a design scenario with which they were involved to determine processes and activities in relation to capture, share and reuse of knowledge. These scenarios could be a modification, a change due to failure, a novel design or a revised design for a new product. Of particular interest were sources of information, channels of communication, critical problems and potential solutions.

Three barriers - technological, capture / storage and sharing / retrieval / reuse - were identified in the results. Technological barriers were due to lack of stability, durability and robustness in the systems. This resulted in a preference for face-to-face communication. Capture and storage barriers related to knowing what to capture, the required level and the relevance. Only design rationale with a successful outcome tended to be documented. A large amount of knowledge tended to be retained in the heads of the designers. Sharing, retrieval and reuse barriers were mainly due to organisational, social and cultural reasons. These included trust in the design and perceived ownership of the design and the preference of designers to design rather than reuse. Where reuse information was available, there was a tendency for it not to transfer to other projects. Design knowledge itself is located in a number of systems, both social and technical. However, informal networks and communities of practice were shown to be very important in the distribution of information.

Thirty four requirements were generated from the interviews to satisfy social and technical requirements. The three considered for the next stage of research were to 'build confidence in data / knowledge captured', 'classification to enable information to be indexed for reuse' and 'allow identification and finding of expertise.' A Knowledge Tool for Designers (KTFD) was proposed and in the process of development to support this, which was a database with multiple views (product, process, etc.). An important consideration in further developments was allocation between technology and human. The development of a pilot system was planned for further work.

2.8.2 Ontology

Bradfield and Gao developed an ontology for knowledge sharing during new product introduction (Bradfield and Gao, 2007). Unlike the other examples of ontology discussed previously, the emphasis was on creating a common understanding for the benefit of the people within the organisation rather than software compatibility. They used the creation of an ontology as a means of standardising (and hence creating a shared understanding) the knowledge about and pertaining to the new product introduction process. The issues of ‘thought worlds’ was not specifically referenced but was noted, with this being seen as a problem to be solved.

2.8.3 Business Methods

The work by Speel et al and Hall and Andriani present a more structured approach to identifying strategic knowledge gaps. Speel et al’s is aimed at business knowledge in general; whereas Hall and Andriani’s is aimed specifically at new product development. Neither approach considers manufacturing knowledge or the preliminary design stage specifically, however their approaches are worthy of note.

Speel et al demonstrate the technique of ‘knowledge structuring’ and its use in creating knowledge maps in Unilever to determine the extent of known and unknown business knowledge (Speel et al., 1999). The objective of the technique is to take a systematic approach to capturing and representing explicit knowledge. The knowledge is represented graphically in a ‘knowledge map’. This graphical format has been found to be useful for human – human communication, for the investigation of modelling techniques by knowledge engineers, to validate knowledge requirements, to specify knowledge-based system requirements and for discussions with business managers.

The two methods used for capturing knowledge are Quality Function Deployment (QFD) and the Causal Knowledge Framework. QFD is a quality management technique used to translate customer requirements into product requirements and to specify the technology options required for the realisation of the product. The requirements are summarised and visualised as a matrix of product attributes against methods for their achievement. In the context of this research they have been adapted. They are used to identify ‘what is known’ against ‘what is not known’. If the space on the matrix cannot be filled, it is defined as a knowledge gap, which is then assessed and ranked. The causal knowledge framework is another matrix which compares problems to causes. The aim of the framework is to give an overview of the knowledge required for strategic development of the chosen area. Both techniques are used in interactive workshop sessions which are facilitated by knowledge engineers with contributions from cross-functional domain experts.

The original purpose of the workshops and the knowledge capture tools were to capture explicit knowledge. However, it was found that ad-hoc tacit knowledge sharing was also occurring outside the main workshop, for example during breaks. They therefore concluded that it was important to create an environment in which this could occur, acknowledging that not all knowledge can be created explicitly. Some factors which influence this environment were a mutual benefit to all participants, the involvement of the ‘best experts’ in their field, the allowance for different perspectives and the reaching of a consensus.

Hall and Andriani also adopted the concept and theories of KM into a new technique for sharing knowledge in new product introduction (Hall and Andriani, 1998). The aim of the technique was to identify the strategic vulnerability in new product development projects by comparing the knowledge required to the knowledge available and equating this to the nature of the knowledge (tacit / explicit). A theoretical model of 'knowledge space' was derived from Nonaka's SECI model and Boisot and Cox's I-Space model (Boisot and Cox, 1999) which was then developed into a methodology which operationalised knowledge management techniques. This was tested on a new product development project (a strimmer) at Flymo.

The model of 'knowledge space' is seen in figure 2.6. The Consciously codified axis refers to tacit / explicit spectrum. The Diffusion axis is the degree to which knowledge has been communicated: individual to individual, individual to group, group to individual. The Mindset axis refers to Discontinous Learning, defined as not 'learning to do things better' but 'learning to do better things'. This takes place in the presence of radical knowledge change where a new knowledge base is needed to replace an old knowledge base.

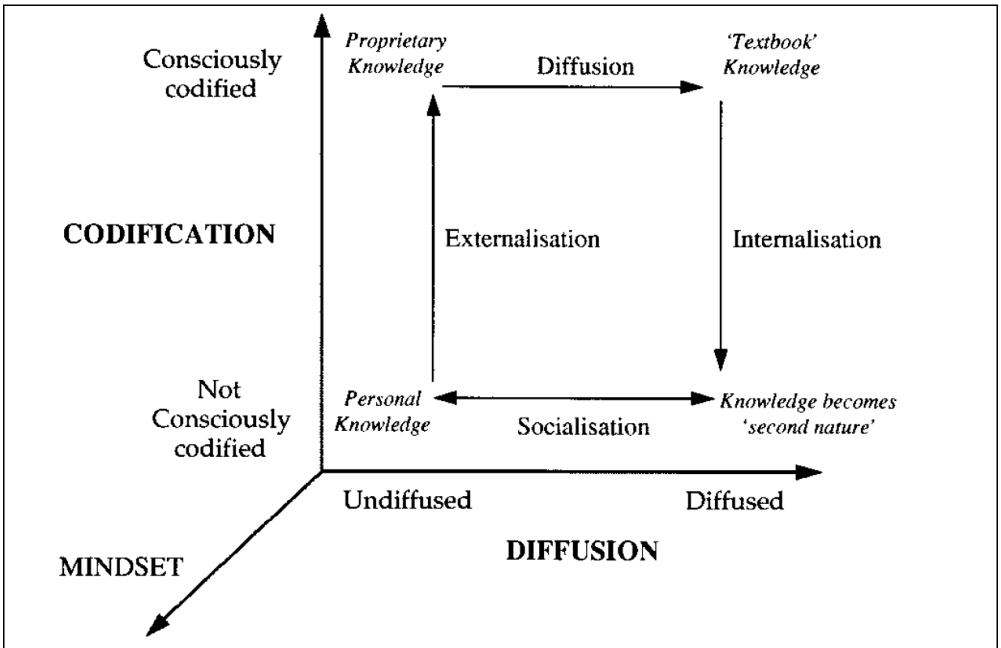


Fig. 2. Knowledge Space [Adapted from Nonaka (1994) and Boisot (1995)].

Figure 2.6: Hall and Andriani's Knowledge Space (Hall and Andriani, 1998)

1) Codified high, tacit low: externally vulnerable, internally safe.
2) Codified high, tacit high: externally safe, internally vulnerable.
3) Codified and tacit low: no competitive advantage.
4) Codified low, tacit high: internally and externally vulnerable.

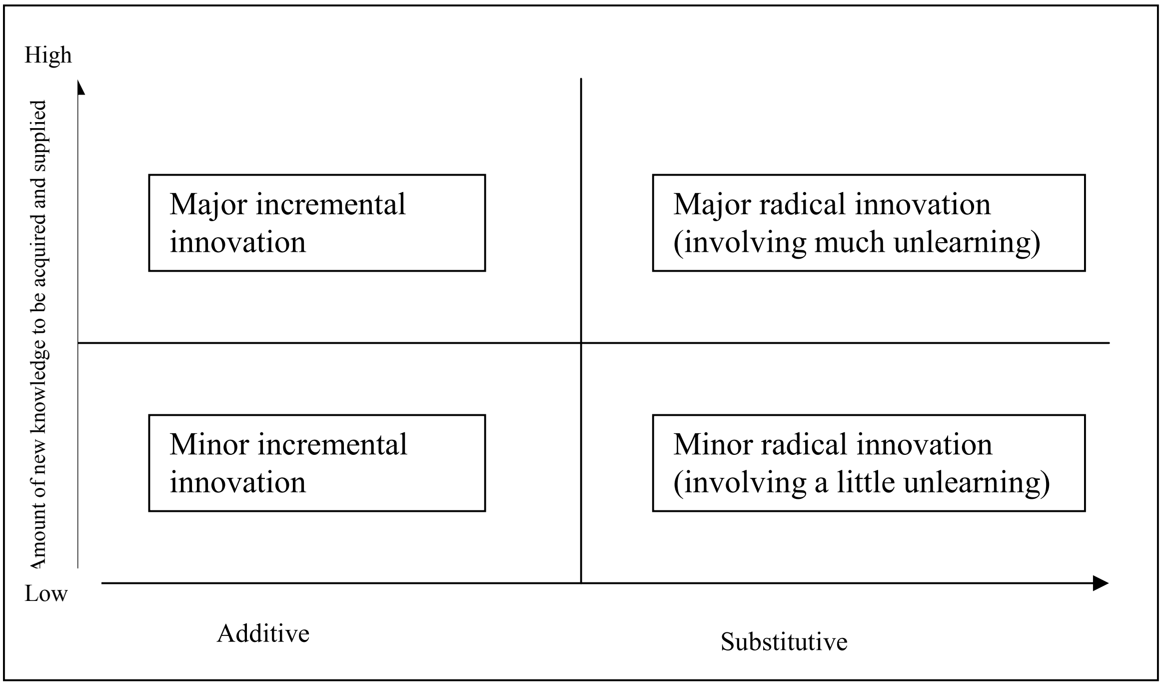


Figure 2.7: Hall and Andriani's Innovation Plot (Hall and Andriani, 1998)

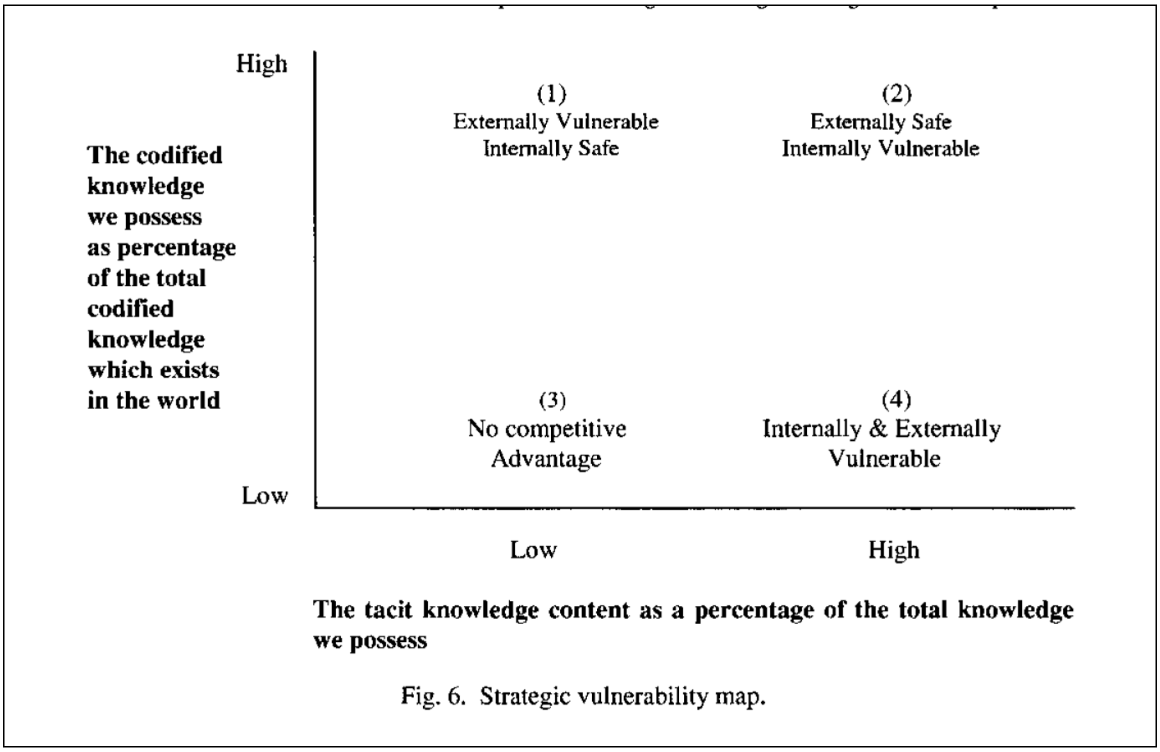


Figure 2.8: Strategic Vulnerability Map (Hall and Andriani, 1998)

Table 2.6: Identification of Tacit and Explicit Knowledge (Hall and Andriani, 1998)

Table 1: Statements designed to identify the nature of the knowledge associated with each unit of analysis.

- We have no knowledge: we need to find the answer by trial and error.
- We have only tacit* knowledge in the form of personal knowledge held by a few individuals.
- We have diffused tacit knowledge contained in embedded organisational routines.
- Explicit / theoretical knowledge exists but the firm has not used it.
- Explicit knowledge is held by a few specialists.
- Explicit knowledge is held in the firm and contained in explicit organisational procedures. Whilst a protocol exists for using the explicit knowledge, practice may involve tacit knowledge in addition to the explicit knowledge contained in the protocols.

The tacit knowledge content* is high( ) medium ( ) low ( )

- Tried and tested theoretical knowledge is held in the firm. The outcome of new circumstances can be predicted; simulation is possible. Whilst tried and tested theoretical knowledge is held in the firm, practice may involve tacit knowledge in addition to the explicit knowledge contained in the theory.

The tacit knowledge content* is high ( ) medium ( ) low ( )

'The tacit / explicit content of a body of knowledge may be determined by means of questions such as the following:
"Can the work be easily sub-contracted? How easy is it to communicate them (sic) knowledge of how to do the job?"
Easy: low tacit knowledge (or tacit knowledge is diffused to potential sub-contractors).
Difficult: high tacit knowledge.
"Does it take a long time for an educationally qualified person to become expert in the area?"
A short time: low tacit knowledge content.
A long time: high tacit knowledge content.
"If something goes wrong, are there explicit organisational routines which will tell one how to put it right?"
If "yes": high explicit knowledge.
"Does theory exist which can predict what will happen in new circumstances?"
If "yes": high explicit knowledge.'

Two questions are then asked concerning the knowledge gaps identified:-
'Of the total codified knowledge which exists in the world, do we have a low, medium or high proportion?'
'Of the total knowledge (tacit as well as explicit) which we possess, is the proportion which is tacit low, medium or high?'

Table 2.7: Results from Flymo Case Study (Hall and Andriani, 1998)

Units of analysis	Type of knowledge
Industrial design challenge	Explicit knowledge is held in the firm…it is supported by a large base of tacit knowledge.
Technical challenges	Diffused tacit knowledge contained in embedded organisation routines.
Communication challenges with customers:-	
Business to business	There is only tacit knowledge held by a few individuals.
End-users	There is no knowledge – it had to be created.
CAD communication challenge	Explicit knowledge exists – it is held by a few individuals.
Partnership challenge	What little knowledge exists was tacit and held by a few individuals who had experienced partnering with suppliers.

Three areas of the project are analysed in the operationalised technique: the brief originating from marketing or a supplier, depending on whether the situation is 'market pull' or 'technology push'; the features required to deliver the vision (where new knowledge needs to be created and these need to be identified early) and the knowledge gaps which represent the missing knowledge which is needed to produce each feature. The researchers stress that successful identification of these 'unknowns' (which may require iteration) is critical to the success of the project. Additionally two other factors are considered: the extent of innovation and the nature of knowledge. The first is defined according to radical and incremental according to the innovation plot shown in figure 2.7. The top right hand corner can indicate difficult / risky projects which have a higher risk of failure. The second is assessed using table 2.6. The results are then plotted on two axes against each other on a two-by-two matrix to give an innovation plot with the following four sectors (see fig 2.8).

Relevant knowledge communities are also identified within the organisation according to the extent of innovation. Where innovation is incremental, the communities may be part of the organisational structure. Communities for 'radical innovation' may be more informal.

The technique was tested on a case study with Flymo. A new industrial designer had created a dual function tool. Table 2.7 shows the units of analysis (knowledge gaps) identified and the related types of knowledge (reproduced). They then plotted the results on a strategic vulnerability map. Examples of knowledge transformation seen were knowledge transfer and knowledge creation, primarily from tacit to explicit. As can be seen, the knowledge types ranged. *'The fact that the knowledge associated with the Technical Challenges was classed as largely tacit appears to be paradoxical, however, it was identified as tacit because the original explicit knowledge had been internalised and had become "second nature". Indeed, in subsequent discussion with the R&D Director of Flymo, he explained that they preferred to operate in the tacit domain as progress was faster and more flexible.'*

Although this research considered the whole product introduction process, some findings are relevant to this thesis. In particular, the innovation plot in figure 2.7 can be used to scope of manufacturing process innovation considered. Depending on the process development required, it can be classified as either major incremental (introduction of a production process not previously used) or minor incremental (development of an existing manufacturing process for new components and / or materials).

2.9 Summary and Identification of Research Gaps

The literature review has highlighted the following areas:-

- There are three main definitions of knowledge which define how knowledge is managed and used. Furthermore, the suitability for specific knowledge types in specific situations varies according to the situation.

- There is evidence of each of the three definitions of knowledge being applied to an engineering design process, particularly for sharing manufacturing knowledge. Again, the way in which knowledge is defined affects how it should be used. Two key themes emerge: the ability to share knowledge across different domains and the ability of the knowledge to describe innovation.

- Manufacturing knowledge content has been mainly been described as process, process capability and cost. Other researchers have expanded this to consider manufacturing resource facilities.

- It is recognised that manufacturing knowledge will become more abstracted earlier in the design process although this is not defined to any extent.

- The two approaches to knowledge management – commodity and community – have both been applied to the design process.

- The commodity approach is effective for knowledge representation in a knowledge re-use or process automation situation. It is also very strong in solving problems in interoperability. It is best suited to a stable product and / or process environment and variant design. It has limitations in a situation where innovation is required, for example in product adaptation or process development.

- The community approach discusses some techniques for tacit knowledge sharing and acknowledges the need for tacit knowledge in innovation. An important aspect of this approach is the sharing of knowledge across cross-functional boundaries which has been demonstrated, for example, by the use of cross-functional teams in concurrent engineering.

- The development of complex mechanical products requires knowledge management techniques which incorporate the sharing of tacit and explicit knowledge. Tacit knowledge is particularly important during the preliminary stage of the design process where there may be inherent risks due to the adaptive nature of the design, innovation requirements and other 'unknowns'. However, engineering knowledge is also systematic and quantitative nature and needs to be captured, processed and controlled by codification. An approach which combines aspects of both the commodity and community approaches is therefore required.

- Two methods of combining the commodity and community approaches have been explored. The first - sociotechnical design – is primarily concerned with the allocation of knowledge to appropriate methods and ways of working. It does not provide a prescribed solution to knowledge management in a specific process. The second, a more structured approach, could present a potential solution in terms of the rigorous and systematic capture of explicit information. This method could also be designed to incorporate methods of tacit knowledge sharing. However, it has not been demonstrated for innovative manufacturing knowledge in preliminary design.

The following research gaps have been identified:-

1. A detailed definition of the content and level of manufacturing knowledge required for the preliminary design stage of the design process.

2. The need to incorporate knowledge about the development of new manufacturing processes (hereafter referred to as 'innovative manufacturing knowledge') Such processes are categorised in this thesis as 'immature' because their capabilities cannot be codified.

3. Although a combined commodity / community approach would be a suitable solution for managing the sharing of innovative manufacturing knowledge during the preliminary design stage, there is no evidence of any techniques being developed specifically for this purpose.

As seen from the literature, these research gaps are particularly relevant to technology-intensive industries and the nature of the components (complex and mechanical) which they produce. This is for two reasons. The first is that the development of new products within these organisations requires some degree of adaptive design and innovation, often with manufacturing processes. The second reason is the need for more effective knowledge management to deal with the complexity of the components produced and the procedures used in their development. In the next chapter the research aims and objectives to address these research gaps are formulated and discussed, together with an overview of the approach to and design of the research study.

Chapter 3

Research Objectives and Methodology

3.1 Introduction

In this chapter, the research gaps identified in the literature are formulated into the research aims and objectives for the study. The methods by which these objectives can be addressed are then considered, discussed and selected.

Three research gaps had emerged from the literature review which warranted further investigation. The first gap was the difference in detail in knowledge requirements for different stages of the design process. The literature had defined knowledge for the preliminary design stage as being 'more abstract'. What did this mean in terms of manufacturing knowledge, particularly in the context of complex mechanical components? In order to define this 'abstract' preliminary manufacturing knowledge content, one needed to understand its impact on a design during the preliminary design stage. This in turn would lead to a greater understanding of the manufacturing knowledge requirements needed to support this stage of the design process.

The second research gap was concerned with how to manage knowledge about innovative manufacturing processes and was particularly important for complex mechanical components. The final research gap was concerned with the use of a combined commodity and community approach for sharing manufacturing knowledge for preliminary design. Both of these research gaps emerged because innovative knowledge was seen as requiring both explicit and tacit elements of knowledge for its successful management. Consequently, not only was the knowledge content requirements important, but also a better understanding of the knowledge types required to convey it. The research aim therefore emerged from these research gaps, addressing the need to explore the nature of manufacturing knowledge for preliminary design and its effective sharing in more detail.

3.2 Research Aim

The aim of this research study is to investigate the nature of manufacturing knowledge required for preliminary design and how these requirements can be identified, acquired and shared effectively between the specialist design and manufacturing domains. The research is specifically concerned with innovative manufacturing knowledge for the preliminary design of complex mechanical components. It takes place within the collaborating company.

Highlighting the scope of the project:-

- The manufacturing knowledge requirements are to be considered at component level, therefore the processes will be mainly primary manufacturing processes (those that are instrumental in forming the shape of the component). These manufacturing processes may be undergoing some development work ('innovative manufacturing knowledge').
- The components will be complex mechanical components which typically undergo some degree of adaptive design for new product introduction projects.
- The study takes place within a single organisation with manufacturing processes and components which display this behaviour, thus creating the potential for a deep analysis of the subject.

Figure 3.1 shows the positioning of the research. It has been adapted from McMahon et al's Perspectives on Knowledge Management for engineering design (McMahon et al., 2004).

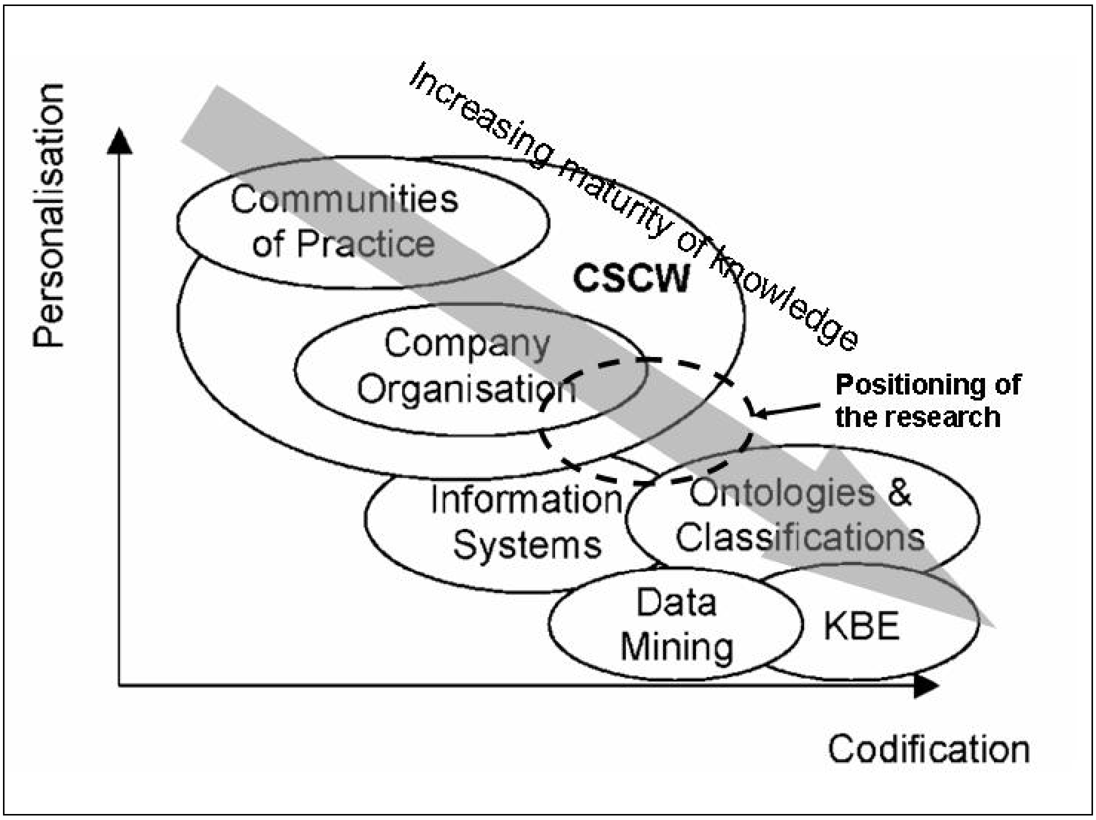


Figure 3.1: Positioning of Research (following from McMahon et al., 2004 and Bohn, 1994)

The diagram shows the main research areas concerned with knowledge management in engineering design and how the knowledge managed by these research areas can be perceived as being personalised (tacit) or codified (explicit). The propensity of knowledge to move from explicit to tacit as its maturity increases (Bohn, 1994) has also been added to the diagram. As this research study is concerned with a combined approach to knowledge management, it is positioned in the diagram where both personified and codified knowledge is of interest.

Rather than being situated in a single area of expertise, this research is positioned at an intersection of several research areas: company organisation, computer-supported collaborative working, information systems and ontologies and classifications. This is because the research aim encompasses features from each of these areas. Firstly, the study will investigate methods which can be utilised using the company organisation and business processes to promote knowledge identification, acquisition and sharing. Such methods could have the potential to be developed into an information system. Furthermore, the identification of the manufacturing knowledge requirements could form a foundation for the development of an ontology.

3.3 Research Objectives

The research aim contains elements of investigation, synthesis and evaluation:-

- Investigation: identification of knowledge requirements, their acquisition and sharing;
- Synthesis: development of a method to achieve this;
- Evaluation: evaluating the method developed.

The research aim therefore needed to be sub-divided into several research objectives in order to achieve each of these elements. Four research objectives were therefore formulated in order to achieve the overall aim. The first two objectives are concerned with identifying the knowledge requirements for the context of the study. The third and fourth objectives are concerned with demonstrating effective knowledge sharing.

The research objectives are:-

1. To investigate the nature of manufacturing knowledge required for preliminary design.

2. To investigate the manufacturing knowledge requirements for an innovative manufacturing process during the preliminary stage of design.

3. To develop a method of effectively identifying, acquiring and sharing the knowledge requirements (derived through objectives 1 and 2) between domain experts.

4. To evaluate whether the method developed in objective 3 presents an effective way of identifying, acquiring and sharing the knowledge requirements between domain experts.

Research objectives 1 and 2 are inductive, creating a hypothesis of manufacturing knowledge requirements. Objectives 3 and 4 test the hypothesis by creating and evaluating a methodology generated from the first two objectives. Each research objective was established as a consequence of the analysis of the previous objective and emerged over time. Thus a flexible, data-driven design was adopted. The research strategies employed for each research objective were decided in the context of this overall approach to the research design. The outcome of each objective then governed the formation of the next objective and its research strategy. The research design approaches and strategies are shown in figure 3.2, together with the research outcome for each objective. They will be discussed in the subsequent sections.

3.4 Approach to the Research Design

As described by Robson, the approach to research design can be fixed or flexible (Robson, 2002). With a fixed design, the details of the study, such as the theory to be used, the details of each case, unit of analysis and methods of collection and analysis are decided before the data collection commences. Consequently any changes to the approach or research design may be difficult later and may result in a redesign of the study. With a flexible design, there may be some initial planning and investigation to design an initial outline study, however subsequent research strategies are shaped by the analysis of data collection. The research design is said to emerge during data collection and analysis.

There are two main approaches to the way in which a study should be conducted. The first approach is often described as positivist (Robson, 2002; Easterby-Smith et al., 1991). This approach has originated from research in science and is seen as the scientific method. The purpose of the approach is to establish facts, which are an absolute truth, value free and independent of social construct. A series of experiments are designed to test a hypothesis. During the experimentation certain conditions are specified and controlled within a laboratory environment. Data is usually quantitative and subject to statistical analysis to either prove or disprove the hypothesis. Typically a causal link will be established. The archetypal scientific laboratory experiment is an example of a fixed research design.

The second approach has various terms – Robson uses interpretive and inductive, Easterby-Smith et al phenomenological (Robson, 2002; Easterby-Smith et al., 1991). With this approach, facts and values are inter-related and subject to social construct, therefore there is no concept of absolute truth and the facts are relative to the context. The purpose of this method is to examine the meaning of situations in great depth, acknowledging that situations in the real world cannot be subject to control as in the laboratory. With this approach, hypotheses are constructed from the collection and analysis of data. Data is usually qualitative and the approach is suited a flexible research design.

Two factors were considered in the selection of the research approach. The first was the nature of the research objectives. They seek an increased understanding of a particular situation and are consequently exploratory in nature. The second factor was the type of data likely to be explored during the study. This thesis adopts Nonaka's view of organisational knowledge in that it is created from the knowledge of individuals. Although technical knowledge is often seen as fact, this study recognises that during the design process it is likely to be derived from the knowledge of engineers associated with design and manufacturing. Consequently a qualitative and interpretive approach would be beneficial in exploring the themes and interactions emerging from these exchanges to create technical knowledge. Therefore a flexible research design has been adopted.

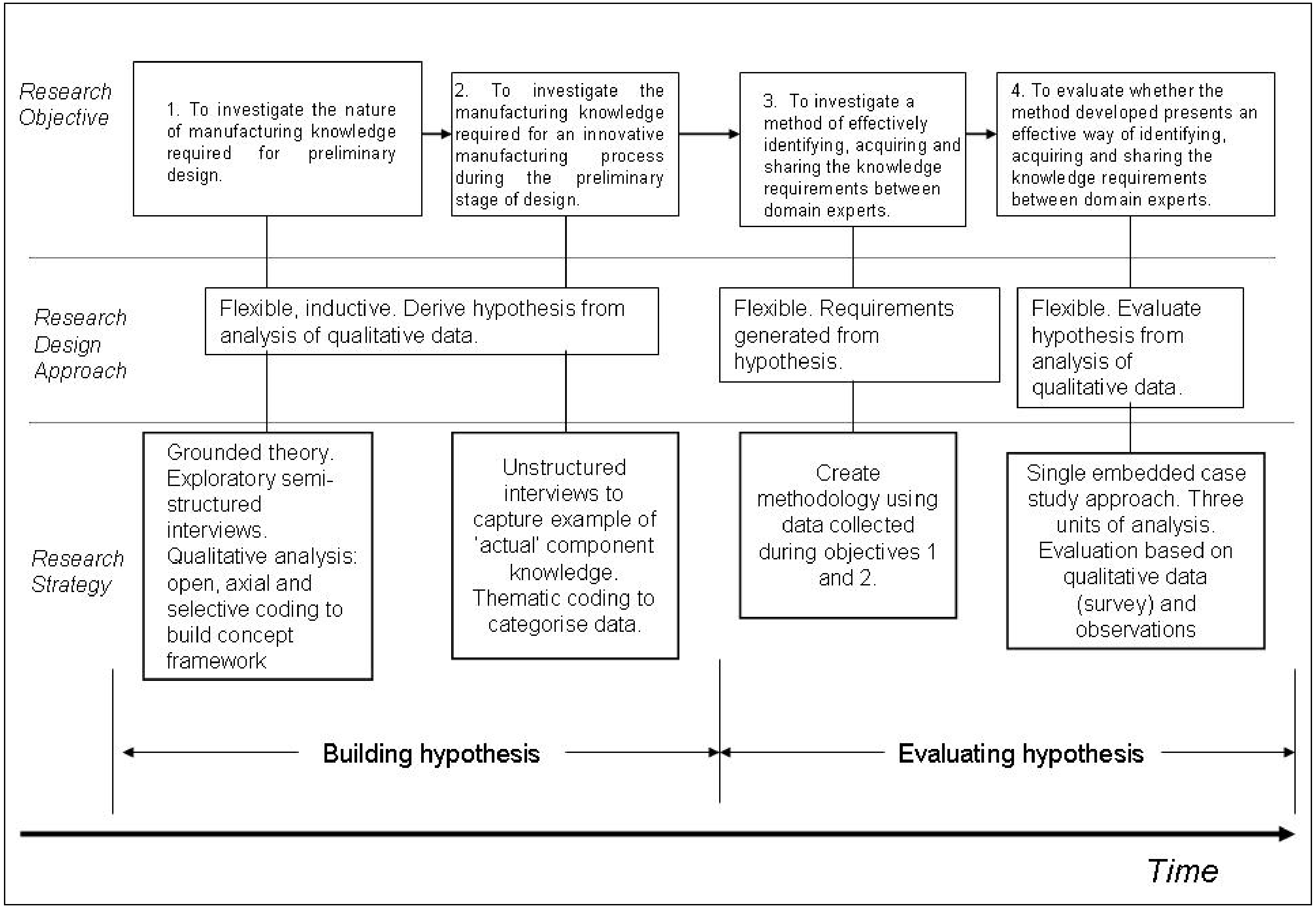


Figure 3.2: Research Objectives, Design Approaches and Strategies

3.5 Research Strategies

The appropriate research strategy depends on the overall research design adopted for the study. For a flexible design, there are three main strategies: ethnography, case study and grounded theory (Robson, 2002). Ethnography is the study of a specific group or community for the purpose of discovering specific features about life in the community. Such study takes place over a prolonged period of time and often involves observation methods to collect the data. The researcher is embedded in the community during the data collection period. Case study research is the detailed study of a pre-defined number of cases. The aim of case study is to examine the application of a specific theory in context, in order to generate a deeper understanding of a situation than can be obtained by other methods (Yin, 2003). A range of data collection and analysis techniques may be used. Grounded theory is used to build theory using several systematic coding techniques from the analysis of data, usually obtained from interviews. This typically involves detailed line-by-line examination of interview transcripts (Strauss and Corbin).

In selecting a suitable research strategy, four influencing factors were considered: the nature of each of the research objectives; the context in which the research was to take place; access and exposure to suitable data and the resulting analysis and use of the data collected.

For research objectives 1 and 2 an exploratory approach was required for a greater understanding of the nature of manufacturing knowledge within the context of the study. Although guidelines could be taken from the literature, there were no pre-existing theories to shape the study.

The decision was taken to concentrate the study within the context of a single organisation. This is recognised as a risk because it limits how the findings can be generalised (see section 3.5.3). However it also created an opportunity in that a situation could be explored in great depth with both inductive and hypothesis testing elements built to the study within the time limitations of the project. Consequently the research strategies adopted would need to be able to generate rich sources of data for subsequent analysis.

The researcher was in a position of being based within the organisation. Theoretically this presented an ideal opportunity for prolonged data from a number of sources. In practice, it was found that this could be curtailed by the availability of data sources due to the demands on staff resources due to the organisation's ongoing projects. Access to data very much depended on the presence of a strong gatekeeper who could use the informal social network within the organisation to make suitable contacts (see chapter 4). Being based in a specific department did not automatically mean that access to other departments would be granted.

In terms of the analysis and subsequent use of the data, the need to utilise strategies to produce rich data sources has already been discussed.

Grounded theory was selected as the most suitable research strategy in which to address objective 1. This strategy is compatible with both the exploratory nature of the research question and the organisational scope for the study. In grounded theory, analysis is interspersed with interviews. The number of required interviews is also flexible and depends on reaching a saturation of data (Strauss and Corbin, 1998). This gives flexibility in scheduling interviews with company resources. This strategy is discussed further in section 4.2.1.

The ethnographic approach, although attractive, was discounted due to the practicalities of being involved with different departments for the extended duration required for the approach. The use of case study for the first research objective was also unsuitable. Despite Robson referring to the use of case study as a method for a flexible research design, when Yin's definition is examined it appears almost as a fixed design (Yin, 2003). A pre-requisite to the undertaking of a case study is an existing theory, even in the sketchiest terms for an exploratory study. This was not applicable for the first research question.

The subsequent research objectives demanded different approaches using the same selection criteria. The second objective was also exploratory, capturing a range of knowledge requirements. It did not fit rigidly with the grounded theory strategy used in objective 1 and required a more flexible approach to data collection from the researcher. Unstructured interviews were therefore selected to provide this flexibility. The analysis necessitated the organisation of manufacturing knowledge requirements into a coherent and organised structure. Further categorisation of the data was also undertaken using the code developed from the analysis of the first data collection.

Together, the analyses from research objectives 1 and 2 generated a hypothesis in the form of a conceptual framework of manufacturing knowledge requirements for preliminary design. This concluded the inductive phase of the study. The conceptual framework therefore needed evaluation during the hypothesis testing part of the study. A methodology was therefore developed using the requirements generated from the conceptual framework to address research objective 3.

For the final objective, an approach was required which was suitable for an evaluation of the methodology, which would in turn evaluate the conceptual framework. A single-case embedded case study approach was therefore selected as a suitable strategy for the evaluation exercise (Yin, 2003). Three units of analysis were considered for the case study. Each unit of analysis was a component and two methods of manufacture for the component. The evaluation techniques used were qualitative and are discussed further in chapter 7.

3.6 Validity, Reliability and Generalisability

It is essential to establish 'trustworthiness' in any research design. In a quantitative study this is achieved by standard tests of replication. With a qualitative design study the principles of validity, reliability and generalisability need to be demonstrated (Robson, 2002). Verification of the ideas generated from the research is also required (Easterby-Smith et al., 1991).

The definitions of validity and verification are of particular interest in this research study because these terms have converse definitions depending on whether they are considered in engineering or research methodology contexts. These are summarised in table 3.1. This study uses the research methodology definitions. A discussion of validity, verification, generalisability and reliability and how they were considered in the study follows.

Table 3.1: Differing definitions of verification and validation

Definiton	Engineering	Research Methodology (qualitative)
Verification	Ensuring the accuracy of the behaviour of the finished product, system or process in terms of its original specification (i.e. 'doing it right') (Moir and Seabridge, 2004; Roache, 1988).	The testing of a generated hypothesis to ensure that it is describing or modelling a situation accurately (i.e. 'doing the right thing') (Easterby-Smith et al, 1991).
Validation	Testing a finished product, process or product to ensure that the original design brief and working solution are appropriate (i.e. 'doing the right thing) (Moir and Seabridge, 2004; Roache, 1988).	Ensuring the accuracy of data collected (i.e. 'doing it right') (Robson, 2002).

3.6.1 Validity

From the context of a qualitative research methodology, the validity of a research design relates to the accuracy of the data collected. A threat to validity is therefore a situation which would affect the accuracy or completeness of data collected. Examples are not recording notes accurately or fully, imposing ideas on the data analysis rather than allowing the main themes to emerge and ignoring possible alternative understandings of the data (Robson, 2002). Such issues need to be considered and designed out of the individual research techniques used for each phase of the study.

Validity can also be affected by the presence of bias, of which there are three types – reactive, respondent and researcher. Bias is said to be *reactive* where the research situation itself can interfere with the validity of the data collected. Data can also be affected by the attitude of the *respondent* and indeed the *researcher* themselves in terms of their understandings and assumptions about the research situation (Robson, 2002).

In line with suggestions from Robson, the following techniques have been built into the research design to minimise bias.

Prolonged involvement

The researcher was based within the collaborating company for 2 ½ years during the research project. This assisted in reducing both reactive and respondent bias by building up relationships based on trust with a number of key stakeholders during this time. However, it is recognised that this technique can increase researcher bias as the researcher can find it difficult to retain objectivity for the duration of the study. Therefore other techniques are also required.

Triangulation

Triangulation is the use of more than one perspective in order to retain objectivity during the research study. It is intended to reduce all three types of bias.

There are four main techniques for triangulation. Data triangulation is defined by Robson as using more than one method of data collection (Robson, 2002), however Patton interprets data collection as meaning *'the use of a variety of data sources in a study, for example, interviewing people in different status positions or with different points of view'* (Patton, 1987, p.60). Observer triangulation refers to the use of more than one researcher for data collection. Methodological triangulation refers to a mix of qualitative and quantitative methods. Theory triangulation refers to using more than one theory.

In the case of this research design, data triangulation was employed in the techniques for research objectives 1 -3 by the selection of people from a mix of disciplines – preliminary design, sub-system design, manufacturing technology, manufacturing engineering and other stakeholder disciplines. This was also the case for research question 4 (an evaluation study), however observations were also recorded in addition to respondent surveys for data collection purposes.

Peer debriefing and support

This technique was also used in the research design to reduce the possible researcher bias created by long-term involvement with the collaborating company. This entails feeding back the results of the data collection and analysis to the original participants as an additional check.

For research objective 1, data was collected through the use of semi-structured interviews which were recorded and transcribed. Each interviewee checked the transcription. Following the analysis of the results, two feedback sessions were held, one for each set of interviewees. Here the results were presented and discussed with the interviewees for their feedback and to see if they were in agreement with the results as a 'check'.

For the second and third research objectives, peer debriefing also took place, albeit in a more informal and iterative way. As ideas for the methodology developed (research objective 3), a number of feedback sessions took place with the stakeholders following initial data collection.

3.6.2 Verification

There were three main ways in which the hypothesis generated from research objectives 1 and 2 was verified. The first was during the data analysis itself. Following on from suggestions by (Easterby-Smith et al., 1991), data was actively interrogated to seek examples which directly contradicted the developing code. The peer debriefing sessions which followed the data collection also presented an opportunity to confirm the emerging ideas. The evaluation of the methodology (research objective 4) was also an example of verifying the hypothesis.

3.6.3 Reliability

Reliability in research design can be demonstrated by an accurate and thorough use of research design methods and techniques (Robson, 2002). This can be established by the use of an 'audit trail' to trace back the results to the original data sources.

The following techniques have been employed within this project to establish reliability:-

- Reliability of the research design: a consideration of the research methodologies available and their selection based on the research objectives and the practical constraints of the project.
- Reliability of data collection: recording and transcription of interviews, recording of notes of discussions and feedback with participants as research ideas progressed.
- Reliability of analysis: establishing links in the spreadsheets used for data analysis to link the original interview quotation / survey score back to the original data source.
- The use of a log book throughout the project to record notes on meetings, feedback, observations, thoughts and ideas as the research emerged.

3.6.4 Generalisability

Generalisability is the extent to which research findings can be applied to a general situation. There are two types – internal and external generalisability (Robson, 2002).

Internal generalisability refers to the extent to which the conclusions can be generalised within the setting investigated. External generalisability is the extent to which the conclusions can be extended beyond the scope of the original study.

For research objective 1, the saturation of data determined the number of people interviewed. Due to the saturation of data it is proposed that the findings of this part of the research could reasonably apply to other designers and manufacturing specialists within the civil aviation division. Thus, some degree of internal generalisability has been obtained.

This is also the case for the evaluation of the methodology. Three units of analysis (different components and associated processes) were selected in a single-case embedded case study. Purposeful sampling was employed in order to select specific cases for which the methodology was deemed to be suitable (see chapter 7). Therefore the results of the case study can be generalised internally to apply to a range of components which would fulfil the criteria of the purposeful sampling.

Because the research study has taken an in-depth approach to a specific company then the results of the study are only applicable within that case. That said, it is acknowledged that the opportunity to study such a specific case in the amount of depth has contributed to a greater understanding of the generation and use of manufacturing knowledge within that specific setting. It would be an interesting opportunity to extend the study to more aerospace and other industrial settings. This is discussed further in chapter 8.

3.7 Summary

This chapter has presented the main considerations and decisions for the overall research design for the project. The main points of the research design are:-

1. A flexible approach to the research design used to address the exploratory nature of the research objectives.
2. An inductive component of the study, using grounded theory analysis techniques to analyse semi-structured interviews and unstructured interview notes respectively.
3. The creation of a methodology, the requirements for which are guided by the hypothesis proposed by the inductive component.
4. The evaluation of the methodology using a single embedded case study as a ‘hypothesis testing’ component of the overall research design.

The data collection and analysis activities for research objectives 1 and 2 are discussed in chapters 4 and 5 respectively. The creation of the methodology for research objective 3 is featured in chapter 6 and the final evaluation (research objective 4) in chapter 7.

Chapter 4

Innovative Manufacturing Knowledge in Preliminary Design

4.1 Introduction

This chapter deals with the investigative study into manufacturing knowledge in preliminary design which was undertaken to achieve the first research objective.

In terms of the manufacturing knowledge required for preliminary design, the literature review demonstrated the following:-

- Knowledge has tacit and explicit elements. The tacit element is particularly important for knowledge sharing, especially innovative knowledge.
- There is a scale of maturity associated with knowledge.
- Preliminary knowledge is referred to as being 'more abstract' but there is no indication of why this is the case, or how this knowledge differs in detail when compared to manufacturing knowledge at other stages of the design process.

Assumptions could therefore potentially be made about the manufacturing knowledge requirements for preliminary design from the existing literature. Many of these assumptions had arisen as a consequence of investigating other phases of the design process, especially detail design. It was therefore possible that a suitable solution at a detail design level would be inferred as being appropriate for preliminary design when this may not be the case. The author was therefore wary of making these assumptions without exploring them further. Additionally, although assumptions had been found, the review into current research indicated that there were no pre-existing models which could be used as a starting point for further investigation.

The decision was taken to conduct an exploratory case study for the first research objective. In doing this, the research would uncover the definition of manufacturing knowledge required for preliminary design as applicable to the organisation being studied. This could then be compared with prior research in this area.

Alongside the research gaps identified in the literature, the nature of manufacturing knowledge for preliminary design equally emerged as a topic for further investigation in an industrial context at the sponsoring company. The organisation employed many techniques associated with 'best practice' in engineering design: a systematic design process, concurrent engineering processes (including DFM activities and IPTs) and staged gate reviews. However, the majority of their understanding of manufacturing knowledge and its transfer was during the later, detail design stage. There was an opportunity to develop a greater understanding of the manufacturing knowledge required at the early preliminary stage (stage 1) of the process.

This chapter documents an investigative study which was consequently undertaken in the organisation over a period of eleven months. There were three main phases of the investigation: a pilot study, a first interview phase and a second interview phase. Each phase yielded some initial findings which were then developed further by the subsequent phases. The overall timelines for the study are shown in figure 4.1. Although the diagram shows these activities as being linear, in reality it was a gradual and iterative process as new data was explored and previous data revisited. Thus the final analysis emerged over time.

This investigative study was an inductive part of the thesis. Consequently, the structure of this chapter follows an interpretive approach to the collection of the data, its analysis and the eventual generation of a hypothesis based on the analysis of the data. Section 4.2 discusses the design of the study followed by its deployment in section 4.3. Section 4.4 discusses the method for analysing the data and developing the code. Section 4.5 presents and defines the code which emerged from these findings. Section 4.6 analyses and interprets and the code. This results in the generation of a conceptual framework of manufacturing knowledge for preliminary design which is presented as a hypothesis. Section 4.7 is a summary of the chapter.

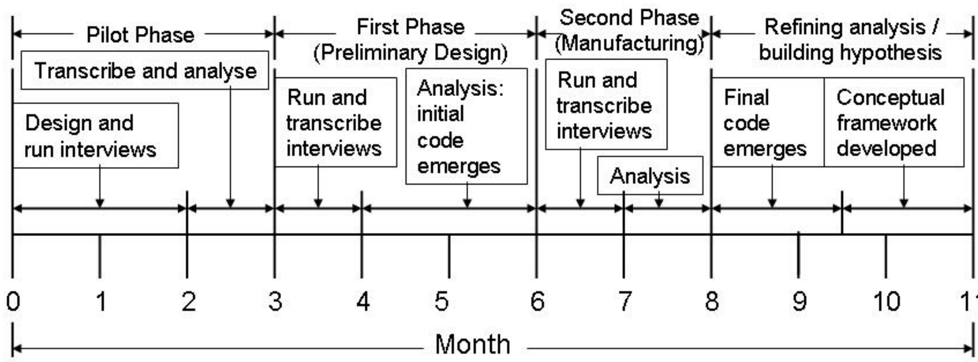


Figure 4.1: Timeline for study

4.2 Research Methodology and Techniques

As discussed in sections 3.3 and 3.4, this data collection represents a flexible, data-driven exploratory stage of the study which is ultimately aimed at developing a hypothesis of innovative manufacturing knowledge sharing requirements for preliminary design. It is concerned with the collection and analysis of qualitative data. The following aspects required consideration in designing the data collection activity: the objective of the activity, how to collect the data, from whom the data should be collected and how it should be analysed. Additionally, research reliability needed to be considered and built into the activity.

Research objective 1 is concerned with exploring the nature of the knowledge. It is concerned with identifying the requirements for knowledge content and examining methods of sharing. Not only is the content important, but also the means by which the knowledge transfer takes place.

This thesis acknowledges and equally considers both the data-information-knowledge hierarchy definition of knowledge and Nonaka's theory of organisational knowledge creation. Manufacturing knowledge for the engineering design process is technical. It is borne from scientific and engineering theorem. It is concerned with establishing fact. However, the mechanisms by which this knowledge is transferred during the design process may be social and have both tacit and explicit components. The knowledge may have therefore have qualitative elements, particularly if it is immature (Bohn, 1994) and may require several modes (including social) for transfer.

The research approach for this part of the study therefore needed to consider these two ways in which knowledge can be defined and also the nature of the problem being considered. The technique selected was grounded theory (discussed in sections 3.5 and 4.2.1), with semi-structured interviews as the technique for collecting the data. These were selected because they would enable the further definition of manufacturing knowledge using a qualitative exploratory technique. The subsequent data-driven analysis would enable a hypothesis to emerge for further development in subsequent research activities towards the investigation of effective knowledge sharing.

4.2.1 Grounded Theory

Grounded theory is a qualitative research technique in which theory emerges from the analysis of data. The aim of the technique is for interpretation and greater understanding of the situation being studied. Consequently it is suited to the investigation of phenomena which have not been defined or interpreted in detail. It is also suited to the phenomenological environment where more than one reality may exist. The technique was developed from social studies and has therefore been used extensively in that area, particularly in healthcare. However, it has also been applied in organisational research (Chell, 1998). It is proposed that this technique is suited to the use in an engineering environment and to this specific study. Although factual and technical knowledge is ultimately sought, research has shown that this may have different interpretations from different departments (Dougherty, 1992). It is also considered to be a useful approach to a situation where there may be a degree of uncertainty in the phenomena being studied.

Grounded theory is an approach to analysing qualitative situations, primarily through the analysis of interviews (although other forms of data collection may also be used). It aims to develop and reveal the meaning behind the occurrence of situations rather than to collate and comment on the purely narrative. It looks for the 'why' in a situation. The way in which the meaning emerges is through a process called coding. Coding is a term used to describe the categorising of the data into particular themes. The connections and relationships between these themes are then explored. This process builds a hypothesis, which can be used to explain how and why specific situations arise and the outcomes which may result. Consequently the hypothesis emerges from the data examined. This hypothesis generally has some degree of abstraction from the actual situations studied because the overall aim is to provide a generalised explanation which is valid for the sample studied.

The process of coding data is approached in a flexible but systematic way. There are three main steps to coding according to the method proposed by Strauss and Corbin: open, axial and selective (Strauss and Corbin, 1998).

Open Coding

This is the initial examination of the data collected from the transcripts of interviews. The transcripts are read and re-read a number of times. The analyst finds that ideas emerge concerning the key points of interest during the interview. Often these are recorded in commentaries alongside the original transcript known as memos. Common patterns begin to emerge in these key points of interest. These can be grouped into specific, identifiable themes. These themes can then be used to group together situations and concepts within the transcript. Thus a theme can be used to categorise these occurrences and highlight their similarities. Being able to describe the data in these more general terms makes the data easier to manage and begins to demonstrate how the themes can potentially apply universally within the sampling context. In developing a theme which is valid across the sampling context, a consensus is sought in all the transcripts by examining whether the phenomena in other interviews also conforms to the emerging themes.

Axial Coding

Once the initial identified themes have been developed into a series of categories, each category is explored and developed in turn. The range of data attributed to each category is investigated. From this, the boundaries of each category are established. This establishes the criteria by which data becomes 'eligible for membership' to that category. As this exploration continues, the dimensions of the category emerge. It may be found that the data in the initial category can be classified further into smaller sub-categories with common dimensions. The boundaries of these sub-categories are therefore also derived, determining when one starts and the other finishes. Consequently, the original category can be sub-divided into a series of sub-categories.

Selective Coding

The first two stages of the coding process consider the abstraction and categorisation of data which separates this data from its original source and context. This final stage of the coding process is concerned with bringing the abstract categories back together in order to create an explanation of the originally documented phenomena.

During this stage the relationships between each category and sub-category are explored. Does one category occur in the same instance as another, for example? What does this say about when and how that instance occurs? By relating these categories to each other, a hypothesis emerges from the data to explain how and why particular situations arise.

Obtaining reliability and validity of the data

In practice, the coding process is very difficult to describe in terms of logical progression and outcomes. Much of it emerges from the coder's own background knowledge and experience. Consequently, some elements of the coding process can be intuitive in that the analyst is relying on their own 'gut instincts' (or perhaps tacit knowledge) as to what constitutes a valid theme and hypothesis. This is accepted by Strauss and Corbin who nonetheless note that there still needs to be some confidence in the validity of the results obtained. They maintain that researchers need to be aware of objectivity and sensitivity in grounded theory and obtaining a balance between the two (Strauss and Corbin, 1998).

Objectivity is required to give an accurate and balanced interpretation of the data. In order to achieve this, the researcher must be able to distance his or herself from the data source and activity. Lack of objectivity can lead to bias. Triangulation from the investigation of multiple viewpoints can be used to achieve objectivity, as can feedback. The researcher must also be sensitive to the data and its subtle meanings in order to identify and link the concepts. The researcher’s own experience and knowledge can be successfully used to develop sensitivity if this is applied appropriately, i.e. used as a foundation for the development of the coding rather than to actively form its development (Strauss and Corbin, 1998).

4.2.2 Selection of the data set

As discussed in section 3.6, in any qualitative study it is necessary to confirm the reliability of the data by achieving saturation, validity and triangulation. The selection of the data set was deliberately designed to achieve this.

The selection of a suitable data set required a different approach to that of quantitative research, where the emphasis is on obtaining a suitable sample size and profile from which the results may be applied to the general population. The reason for the difference is due to the nature of a qualitative study. Qualitative data collection and analysis is concerned with the in-depth exploration of specific situations. The samples selected for analysis are specifically selected to be pertinent to the topic being studied and to be a rich source of data. This is known as theoretical sampling (Strauss and Corbin, 1998). Qualitative data sets are typically smaller than those for quantitative studies. Whereas a quantitative study would seek an ideally representative number of responses, in a qualitative study representation is achieved by data saturation. Data is said to be saturated when no new lines of enquiry are emerging from subsequent datasets. Thus, where quantitative analysis would insist on a statistically valid sample size, the sample size required for a qualitative analysis would be determined by the necessary quantity to achieve saturation.

The data collection activity was designed to be an in-depth study of part of the design process. Therefore the number of interviewees was limited to a small scale study. Two main areas were targeted for the interviews within the collaborating company. The first area targeted was the preliminary design team. Here, interviews were carried out with five preliminary designers, selected from a list. The author did not know any of the team members prior to the interviews. The experience of the interviewees, both prior to and within the preliminary design department varied widely. Usually each of the designers had significant specialist experience with a sub-system design team before moving to the preliminary design team. However, this has not been explored further in the thesis for two reasons. The first reason is that on analysis the differing backgrounds did not have any bearing on the key factors which emerged and were therefore not considered to be relevant for this study. The interest was in specific situations rather than specific people. The second reason is to protect the identity of the participants, who were assured anonymity. As the preliminary design department is relatively small to reveal the background of each of the participants could unwittingly reveal their identity. In the subsequent discussion and analysis of the interviews, the interviewees are referred to as Preliminary Design 1 to 5.

The first analysis and coding took place after the first five interviews. Further interviews were then required to validate and expand this code to other departments which interfaced with the preliminary design department, therefore a second area was targeted. Six interviews were therefore carried out with representatives from departments which interacted with the preliminary design team during the product introduction process. They were four members of the Manufacturing Technology team (a team of manufacturing specialists involved with the development of new methods of manufacturing and technology management) and two representatives from a sub-system design team: a designer and a manufacturing engineer. These participants are referred to in the analysis as Mantech 1 to 4, sub-system designer and sub-system manufacturing engineer respectively. The participants from the second group were often identified by other interviewees as people with whom they had worked and whose experience would be relevant for the interviews. From the second group, only one interviewee was previously known to the author. Again, for the same reasons as the preliminary designers, the range of experience varied but was found to be immaterial and all the participants remained anonymous.

The five preliminary designers were selected to give the preliminary design 'world view'. The additional six interviewees were selected to investigate whether the preliminary designers' view was particular to that group or common across the product introduction process. By selecting the two groups data triangulation was achieved. The subsequent six interviews also achieved saturation in the development of the code.

Before running the two phases of the study, a pilot study was first run which had three objectives. The first was to develop the interview questions. The second was to practice running the interview, its timing, the use of recording equipment and transcribing. The final objective was to begin to develop ideas on how to code each interview. Five interviews were run for this phase. The interviewees were colleagues or friends who were familiar with the research project and were keen to help. Two designers and three people with varying manufacturing experience were interviewed to gauge the range of responses which would emerge from each specialist domain. The first designer had a strong history of design in aerospace components with experience of design at all stages (concept, preliminary and detail) of the design process. The second designer had experience of detail design in large mechanical engineering components. Neither designer had been employed by the sponsoring company, however their generic design knowledge proved to be useful for practicing the interviews and gauging the type of data which may emerge. The three remaining interviewees represented manufacturing and all worked in some capacity for the sponsoring organisation. The first was a manufacturing engineer involved with establishing the manufacturing processes for new components, the second had experience in improving existing manufacturing process methods and the third was involved in the development of new manufacturing technology. Between them, the scope of the interviewees' knowledge covered all stages of the design process and development of manufacturing technology and processes. Anonymity was granted and the data was used purely for the benefit of the researcher in developing the study.

4.2.3 Design of the Interview

The objective of the data collection process was to capture rich qualitative data effectively in a time frame mutually acceptable to the interviewer and interviewee. Semi-structured interviews were selected (see section 3.5) because they were a flexible method of exploring the required discussion points. A core list of questions could be asked but there would be scope to discuss any additional points of interest which could arise during the interview. This technique was also well-suited to a grounded theory-based qualitative coding analysis. The interviews would be conducted face to face and were designed to take place within a time frame of a maximum of an hour and a half. This time was judged to be a compromise in collecting sufficient interview data without too much impact on the interviewee's work commitments.

The interview itself needed to define the manufacturing knowledge required for preliminary design and the methods by which this knowledge was transferred. This needed to be carried out in a way which would address the main concern of the study and enable the designers to identify with the importance of the knowledge. Manufacturing knowledge was therefore defined as an impact (positive or negative) on the design requirements or design outcome due to some aspect of manufacturing and the knowledge required to describe this. During the interview, the interviewees were asked to recall incidents where they had been aware of this impact. This served two purposes. The first was to generate a significant amount of rich data for analysis. The second purpose was to aid effective recollection from the interviewees. The approach used for the interviews is an adaptation of the Critical Incident Technique, originally developed by Flanagan for use in psychology but also applied to organisational research (Flanagan, 1954; Chell, 1998). Chell defines it as:

'a qualitative interview procedure which facilitates the investigation of significant occurrences (events, incidents, processes or issues) identified by the respondent, the way they are managed, and the outcome in terms of perceived effects. The objective is to gain an understanding of the incident from the perspective of the individual, taking into account cognitive, affective and behavioural elements.' (Chell, 1998, p.56).

The approach used in this research is an adaptation of this technique because rather than seeking to interpret the behaviours and actions of the individuals, it seeks to develop a greater understanding of the 'behaviour' of knowledge identification and transfer as a process during design. Because organisational knowledge stems from the interaction of individuals, it is important to understand the contribution of interactions between individuals to overall knowledge generation. The technique has further advantages in that the focus of the interview is on the specific issue to be explored which aids recall from the interviewee. This creates a data-rich source for analysis. The method is also truly data-driven because the interviewees control what is revealed which shapes the outcome of the session and ultimately the emerging theory. It is therefore useful as a comparative tool for more than one interview and can also be a suitable source for developing grounded theory (Chell, 1998).

A set of core questions were developed and refined during the pilot phase and are shown in table 4.1. The purpose of the background questions were to firstly establish the interviewee's background and level of experience (typically preliminary designers have had specialist roles elsewhere in the company first) and to also serve as an 'icebreaker' and establish a rapport with the interviewee. The set of questions are small, however they invoke in-depth replies and also offer scope for expansion to other areas of interest if required.

4.3 Running the Interviews

The methods used to run the interviews were the same for all three stages of the activity. All the interviews were recorded and transcribed to maximise validity. Each record was therefore the interviewee's own words and not the interviewer's initial interpretation. The questions in the interview script were checked for neutrality and the script was adhered to for all interviews.

It was important to solicit as wide a range of responses from the interviewees as possible. It was imperative for the interviewees to not merely 'toe the party line'. Thus, some attempts at establishing neutrality were made in the interview setting. The interviews did take place within the organisation, but in private meeting rooms away from interruptions and away from where answers may be overheard. The author (as interviewer) dressed neutrally, not wearing company-branded workwear. Anonymity of the interviews was guaranteed and permission to record the interview sought before it commenced. There were no refusals. As far as can be ascertained, the responses to the interview appeared to be honest, open and credible.

Table 4.1: Core questions for semi-structured interviews

Background questions:
Tell me about the work you do now. Summarise your background / previous experience. Tell me about the product range you work with. What are the main design requirements for these products? What stages of the product introduction process are relevant to your work?
Select one of your products as an example:
Consider a situation where manufacturing considerations have impacted on the main design requirements or outcome. What was the situation? What was the manufacturing process? What were the design requirements affected? What was the impact on them? At what stage of product introduction process did this occur?
Sources of manufacturing knowledge:
For each example discussed:- How did you know about the situation and its impact? What was the source of the information? In what format was the information? Where was the information stored? How was the information used / re-used?

The interviews lasted between one hour and an hour and a half. The interviews were transcribed. Each interview generated approximately ten pages of A4 paper and took around ten hours to transcribe. Following a suggestion in the first preliminary design interview, all the preliminary design interviewees brought in graphical images of an example product so that they could refer to areas of particular interest.

As has been discussed, validity had been designed into the study primarily by means of data triangulation. Peer feedback sessions also took place with the interviewees following the development of the final code in order to confirm the results. However, it is recognised that some bias may have been inevitable during the process. Although efforts were made to remain neutral with additional (‘off the script’) lines of enquiry, this could not be guaranteed. The author also has a great deal of experience in engineering, especially manufacturing engineering and the design / manufacturing interface. This was highly useful in developing sensitivity to the data for interpreting interview responses and affirming the credibility of the answers. However, it is also recognised that this may have affected their responses to the interviewees.

4.4 Coding the Interviews

This section demonstrates how the analysis evolved during the study.

4.4.1 Pilot Study

The development of the coding was not the main focus of the pilot study, however some preliminary coding activities did take place as practice. There were differences in the industrial contexts sampled between the pilot interviewees and the official interview stages. Consequently the coding was not developed in much detail, with just some preliminary open coding activities being undertaken during this phase. However, there is some worth in commenting on this activity because this did shape the way in which the coding would take place for the official interviews.

Each transcript was read through several times to examine the main themes which were emerging. In line with the question format, two key elements of the data emerged:-

i. The impact of manufacturing on component design.
ii. The way in which this was communicated.

Consequently, two initial categories emerged from a preliminary open-coding activity. The boundaries and dimensions of these categories (axial coding) were not explored any further however. The identification of these two categories led to the development of a template to capture the relevant data from each identified critical incident discussed during phases 1 and 2 of the interviews. The data to be recorded - and the rationale for this - is shown in table 4.2.

Table 4.2: Analysis of Critical Incidents during Pilot Study

a. The interview (anonymously defined by an interview number);
b. Years experience of the interviewee (discounted in later interviews);
c. The design stage at which the incident occurred (this was coded in line with the company understanding of the design process – stage 0 for concept, stage 1 for preliminary, stage 2 for detail design);
d. The component affected;
e. The manufacturing process involved;
f. The situation that occurred;
g. What action was taken;
h. How this impacted on the component design;
i. How the interviewee heard about the situation.

4.4.2 Phase 1: Preliminary Design Interviews

The main focus of the analysis for the first phase was open coding – the development of the main categories. Each interview was read several times. Phrases which were particularly interesting were underlined or highlighted. The transcript was annotated with ideas and comments about possible emergent themes or items of interest. These were initially centred on the critical incidents volunteered and discussed by the interviewees. The following information was identified from each transcript and manually entered and summarised in a Microsoft Excel table in the template shown in table 4.2. Extra categories were added to the table to continue the analysis. These are shown in table 4.3.

Table 4.3: Additional coding for Critical Incidents for Phases 1 and 2

j. The format of how the interviewee heard about the situation;
k. How this information was recorded / stored / used / re-used.
l. Whether there were any alternative sources of information available.

The following information was then compared for all interviews to explore the similarities and differences in the characteristics of each incident:-

m. Characteristics of the situation.
n. How this impacted on the component design.
o. The format and use of information associated with this situation.

The initial identification of themes also produced some interesting points which were not necessarily linked to a specific incident but required further examination. In this case, each individual interview was treated as a unit of analysis. Pertinent comments from each interview transcript were underlined and transferred to an excel spreadsheet. However no further coding took place at this stage (the author felt rather swamped by data at this point and unsure on how to proceed with the extra source).

The main focus of the analysis was the data which related to the critical incidents discussed by each interviewee. Consequently the two main categories which emerged were the same as those for the pilot study: manufacturing impact and knowledge type. However at this stage these two categories were developed using axial coding. The data in each category was examined and each category could be further divided into three sub-categories. For the manufacturing impact, these could be further described as quantified, capability and standardised. There were also three knowledge types described: structured, semi-structured and unstructured. This terminology was derived and applied by the author to describe her particular coding and is not intended to signify or describe anything else. The initial code is shown in appendix B, however it will not be elaborated further because it was subsequently developed into the final version after the second round of interviews. This will be discussed in section 4.5.

4.4.3 Phase 2: Manufacturing Interviews

The coding process also followed the same method as the first phase. Again, each transcript was read repeatedly, with pertinent comments underlined and highlighted. Annotations were added to the transcript to highlight what were judged to be important comments. The critical incidents were added to the table with the data from the first phase of interviews. Again, there were a number of additional comments which were of interest, but not directly related to the critical incidents. These were copied and pasted into the excel spreadsheet together with the additional comments from the first phase.

There were two parts to the coding process for the second phase of interviews. The first was developing the code relating to the critical incidents. The second was making sense of all the additional comments (not directly related to the critical incidents) from both phases of the interview process. Each shall be discussed in turn.

In some ways the coding of the critical incidents was more straightforward for the second phase. This was because the initial set of categories (an initial code) had been developed for the first set of interviews. The purpose of coding in this case was to investigate how the data collected in the second phase fitted the code developed from the first phase. This would confirm or reject the six categories which had been developed for the code. It would also potentially expand the number of sub-categories. In fact, on further examination of the data, the initial categories were expanded to three main categories (and nine subcategories) for the final code. These are presented and discussed in section 4.5.

Open coding was also used to analyse the list of additional comments. Each comment was read and re-read, commented upon and gradually sorted until six main themes emerged. Although they were not directly tied to a specific critical incident, these themes gave some useful background information and were therefore used to support the further development of the critical incident code. They were useful for examining and interpreting the meaning of the developed code and in building the relationships between the three main categories to give the final conceptual framework. This is discussed further in section 4.6.

4.5 Results

This section describes the main outcomes of the open and axial coding stages of the analysis. It describes the categories and subcategories derived from the critical incident data and the main themes to emerge from the additional comments.

As the analysis is data driven, these sections present the definition of the categories from the data supplied in the transcripts. These categories will be explored and interpreted further in section 4.6 to develop a conceptual framework of manufacturing knowledge in preliminary design.

4.5.1 Definition of the Code from the Critical Incidents

Three main categories emerged from the open coding of the interview transcripts. The first was how the selection of the manufacturing process impacts on the component configuration being designed. The second was how the maturity of the manufacturing process (how far it had been developed and how well the process capabilities were known) influenced decisions in manufacturing assessments during preliminary design. The third was how the knowledge had been communicated, with verbal communication featuring strongly. These categories were named the ‘Manufacturing Impact’, the ‘Expression of Manufacturing Impact’ and ‘Knowledge Type’ respectively. Through axial coding, each category was subdivided into three sub-categories. A summary of the code developed is illustrated in table 4.4.

These categories were derived from the data of eighteen critical incidents which were identified in the interviews and are summarised in table 4.5. The incidents are described in terms of the categories developed for each incident (the manufacturing impact, expression of impact and knowledge type). Each incident has a manufacturing impact, an expression of impact and at least one knowledge type associated with it. In some cases all the knowledge types were used to firstly represent and calculate the knowledge and then communicate it to other team members.

The definition of each main category and its associated subcategories follow in sections 4.5.2 to 4.5.4 with quotations from the interviews to illustrate examples of their occurrence. The meaning of each main category and how they inter-relate are discussed in section 4.6.

4.5.2 Category 1: Manufacturing Impact

The manufacturing process ultimately constrains the size and shape of a component being designed. The extent of this constraint can be described in increasing levels of detail. The three sub-themes relate to the level of detail of knowledge described for the manufacturing process.

Sub-category 1: Configuration impact

The configuration manufacturing impact occurs to the exclusion of other impacts in preliminary design. It is suggested that this is because the preliminary design team require knowledge of the effects of the manufacturing process at a component level. More detailed process knowledge (see ‘tooling’ and ‘manufacturing geometry’ impacts) is relevant at the stage where production planning needs to be considered but may not be relevant to the preliminary stage. This is illustrated by the comment below, from a preliminary designer, comparing design activities in preliminary design to a previous role as a designer in a business unit:-

Table 4.4: Summary of Interview Coding

Main Category	Definition	Sub-Category	Definition
1. Manufacturing Impact	Describes how the manufacturing process constrains the size and shape of the component.	Configuration Impact	The constraint is due to manufacturing.
		Tooling Impact	The constraint is due to the machine tool.
		Manufacturing Geometry Impact	The constraint is due to added geometry for manufacturing purposes.
2. Expressions of Manufacturing Impact	Describes and determines the manufacturing impact.	Empirical	An experimental assessment is required.
		Quantified	Can be described within known quantifiable parameters.
		Standardised	Can be described from a list of predetermined standardised sizings.
3. Knowledge Type	Describes the knowledge types used to communicate the expressions of manufacturing impact.	Unstructured	Communicated verbally.
		Semi-structured	Can be expressed as mix of numerics and text. The text adds context.
		Structured	Can be expressed numerically or graphically.

"I've certainly noticed that we still work with manufacturing but it's a bit distant now, because ours is more general rather than the specific, not like can we have this radius fillet here or that, ours now is, have we got the whole engine concept right. It's not necessarily the tolerance levels and things, it's what size is the engine now, what are the limitations on casting sizes, forging sizes, what's the minimum bore you can produce on a shaft, etc." (Preliminary Design interview 4)

Definition: This code occurs when the manufacturing process constrains the size and shape of the component at an overall level by a 'configuration envelope'. The constraints imposed by these parameters must be considered in a trade-off with other design requirements (i.e. sizing limitations from lifing, aerodynamic requirements) with the 'worst case' sizing being the final design case. The constraints can be inferred by considering a previous component (and manufacturing process) as a starting point for the previous design. These constraints may have a positive or negative effect on design creativity.
How to know when the theme occurs: Reference to geometric / shape constraints due to the manufacturing process, or evidence of new geometry due to a new manufacturing technology development. The interviewee may be aware of the manufacturing process but not the specific aspect of the process which is causing this limitation.
Qualification: Any constraint named must at least be described as 'due to manufacturing'. A description of the manufacturing process is a good qualifier, but is not essential. The description should not be too detailed as references to actual process planning considerations are covered by the 'Tooling' and 'Manufacturing geometry' codes.

Table 4.5: Critical Incidents identified in the interviews (1-5)

Critical incident	Interview of origin	Design Stage	Product / feature affected	Manufacturing process	Impact	Impact type (coding)	Expression of impact (coding)	Knowledge type (coding)
1	Preliminary Design 1	0 - 1	Shrouded HP turbine blade	Casting (inferred, not directly stated).	Manufacturing minimums. Design thicker than preferred in order to manufacture, therefore weight penalty which transfers through to discs and containment.	Manufacturing process limits geometry (configuration impact)	Recorded as dimensional rules (quantified)	Verbal conversation with manufacturing process expert (unstructured)
2	Preliminary Design 1	0 - 1	Casing	Not stated	Manufacturing minimums: Trade-off: Thickest dimension from blade off design vs. pressure design vs. manufacturing minimums vs. whole engine modelling loads	Manufacturing process limits geometry (configuration impact)	Recorded as dimensional rules (quantified)	Plum folders - document design rules (structured)
3	Preliminary Design 1	0 - 1	Firtree	Not stated	Manufacturing band tolerances. Tolerances influence how design is modelled. Series of lines and arcs used instead of a smoothline fillet.	Manufacturing process limits geometry (configuration impact)	Recorded as tolerance band rules (quantified)	Not stated - interviewee talks in general about a network (unstructured).
4	Preliminary Design 1	0 - 1	Cover plate	Not stated	Manufacturing band tolerances more relaxed than designed tolerances. Design intent cannot be achieved, therefore design changed.	Manufacturing process limits geometry (configuration impact)	Recorded as tolerance band rules (quantified)	Not stated - interviewee talks in general about a network (unstructured).
5	Preliminary Design 1	0 -1	Curvic coupling	Not stated	Cost of machine tooling limits design sizes, selected from previous designs.	Manufacturing process limits geometry (configuration impact)	Re-use of previous component (standardised).	Not stated - interviewee talks in general about a network (unstructured).

Table 4.5: Critical Incidents identified in the interviews (6-8)

Critical incident.	Interview of origin	Design Stage	Product / feature affected	Manufacturing process	Impact	Impact type (coding)	Expression of impact (coding)	Knowledge type (coding)
6	Preliminary Design 2	0 - 1	HP Compressor drum	Inertia bonding to replace bolts, hence single piece drum. Process selection restricted by material properties	Changing of method of joining constrained as process capability not of sufficient maturity to guarantee production (cost / benefit analysis). Revert to bolted joints.	Manufacturing process limits geometry (configuration impact)	Feasibility based on results of development work (empirical)	Verbal conversation with manufacturing process expert (unstructured)
7	Preliminary Design 2	0 - 1	Curvic coupling	Machining, comparison to master.	Change design to improve component results in potential m/f process change. Not proven technology, in terms of accuracy of manufacturing process and certification for aircraft. Revert to original design, method of manufacture and joining.	Manufacturing process limits geometry (configuation impact)	Feasibility based on results of development work (empirical)	Verbal conversation escalated from build shop through to director of manufacturing and build (unstructured).
8	Preliminary Design 2	0 -1	Engine Section Stator (ESS)	Casting hollow vanes, whole ring considered. Vs. forging and welding assembly as an alternative.	Limitations of process capabilities for alternatives considered: casting limitations of hollow vanes, of casting a whole ring, of spark eroding holes, of forging and welding. Process capability not mature enough, cost implications (esp. with suppliers), so some ideas rejected. Eventually cast. Vanes have to be cast thicker than originally preferred - weight penalty.	New manufacturing process enables new geometry (configuration impact)	Feasibility based on results of development work (empirical)	Not known

Table 4.5: Critical Incidents identified in the interviews (9-13)

Critical incident	Interview of origin	Design Stage	Product / feature affected	Manufacturing process	Impact	Impact type (coding)	Expression of impact (coding)	Knowledge type (coding)
9	Preliminary Design 3	0	bearing support structure	Casting	Constrains size and shape of component. Fabrication considered as an alternative but costs too high. Weight penalty.	New manufacturing process enables new geometry (configuration impact)	Recorded as weight / trade-off calculations (quantified)	Numerical calculations (structured).
10	Preliminary Design 4	0-1	Shaft	Not stated	There is a limit on the bore of the shaft which can be successfully machined. Bore size, hence diameter size, limited. (Torque carrying capability). Performance penalty.	Manufacturing process limits geometry (configuration impact)	Recorded as dimensional rules (quantified).	Not known
11	Preliminary Design 4	0-1	Shaft	Inertia welding	Only process which can be selected to join materials. Not a mature process. Investment required for maturity	New manufacturing process enables new geometry (configuration impact)	Feasibility based on results of development work (empirical)	Not known
12	Preliminary Design 5	1	Ducts, valves, pipes	Not known (process determined by supplier)	Constrains on positioning accessories due to standard sizes. Accepted, not perceived as a problem?	Manufacturing process limits geometry (configuration impact)	Component selected from standard set of component sizes (standardised).	Not known
13	Preliminary Design 5	1	Bend radii, pipe connectors, end fittings	Not known (process determined by supplier)	These are standard features - i.e. limited choice of standard sizes. Constrains on positioning accessories due to standard sizes. Accepted, not perceived as a problem?	Manufacturing process limits geometry (configuration impact)	Component selected from standard set of component sizes (standardised).	Not known

Table 4.5: Critical Incidents identified in the interviews (14-16)

Critical incident	Interview of origin	Design Stage	Product / feature affected	Manufacturing process	Impact	Impact type (coding)	Expression of impact (coding)	Knowledge type (coding)
14	Preliminary Design 5	1	Rear fan case	Composite lay-up type procedure (determined by supplier).	Supplier can select one of two options - a plain skin with a rear stiffener, or a sandwich structure (thicker, stiffer so no need for stiffener). Rear stiffener limits positioning of gearbox and other accessories. Affects how accessories are mounted and access to them.	Manufacturing process limits geometry (configuration impact)	Component selected from standard set of component sizes (standardised).	Not known
15	Mantech3	1-2	HP Compressor drum	Inertia welding	Replaced bolted geometry for two stages	New manufacturing process enables new geometry (configuration impact)	Feasibility based on results of development work (empirical)	Verbal discussion and meeting minutes via IPT (Semi and unstructured)
16	Mantech4	1-2	Blade (for blisk)	Linear friction welding	The fillet rad size is ideally determined by the aerodynamic requirements of the vane, however there's a chordal geometry constraint in the process which must achieved.	Manufacturing process limits geometry (configuration impact)	Expressed as dimensional rules (quantified).	All. Rule chordal geometry vs. fillet size recorded and processed in a key system (structured), recorded in IPT minutes and and discussed in meeting (semi- and unstructured)

Table 4.5: Critical Incidents identified in the interviews (17-18)

Critical incident	Interview of origin	Design Stage	Product / feature affected	Manufacturing process	Impact	Impact type (coding)	Expression of impact (coding)	Knowledge type (coding)
17	Mantech 4	1-2	Blisk	Linear friction welding	Minimum requirements for tooling clearance impact on number of blades which can be fitted on a blisk.	Manufacturing process - specifically tooling access - limits geometry (tooling impact)	Feasibility based on results of development work (empirical)	All. Calculation carried out to determine number of blades (structured), recorded in IPT minutes and and discussed in meeting (semi- and unstructured)
18	Sub-system designer	1-3	IP fixed vanes, shrouds and blades	Machining	Aerofoil is forged with oversize blocks on each side for workholding. Designers try to use same block sizes for standardised workholding	Manufacturing process - specifically added geometry for work holding - limits geometry (manufacturing geometry impact)	Work-holding geometry re-used from previous component (standardised).	Not known.

An example of a situation where the code occurs:-
Minimum allowed wall thickness of a component due to the casting process. A previous assembly becomes a single component.
An example of a situation where the code does *not* occur:-
A component is shaped a certain way due to tooling access. Additional material is added for work holding.

The effect of the configuration impact will vary according to specific manufacturing processes and components. The main feature of this category is that the designers are aware of the impact but not necessarily its cause. As an illustration, critical incident 5 in table 4.5 refers a configuration impact as seen in a component called the curvic coupling. This product has a set of standard sizes to which are used, due to manufacturing process constraints. The design engineers are aware of the size limitations on the component, but not the specific reasons why the manufacturing process has caused this limitation. Investment in new equipment or a different manufacturing process would change these limitations.

Sub-category 1: Tooling Impact

This impact is evident during the detail design stage, where individual process operations are under consideration.

The two following quotations illustrate how tooling access and usage can limit geometry in component design. They are both concerned with the detail stages of design and are from the interview with the sub-system Designer:-

> *'There are a lot of implications in terms of tooling, fixtures, the way the actual machine tools come in and have to get access to various parts of the component to machine it.'*

> *'As the tool wears down, they don't want to machine it all in one go, but because it's very difficult to get it lined up exactly with all the previous cuts, there are mismatches on there, and with this material being a lot harder than it was in the past, the tool's wearing down a lot quicker, so we had to allow more mismatches. But rather than just allow them anywhere we had to understand with stress, that the best way to have the thickness varying is according to the position of these mismatches.'*

Definition: This code occurs when the manufacturing process constrains the size and shape of the component due to tooling clearance limitations at component level.
How to know when the theme occurs: Reference to geometric / shape constraints due to tooling access. The interviewee will have a detailed knowledge of the manufacturing process.
Qualification: An in-depth discussion of the manufacturing process highlighting tooling access constraints.
An example of a situation where the code occurs:-
The geometry of the component is changed to allow clearance for machine tools.

Sub-category 1: Manufacturing Geometry Impact

This manufacturing impact was also identified during the later stages of detail sub-system design where individual process operations are under consideration.

This comment illustrates clearly how the addition of geometry for manufacturing can impact on the design:-

'...and our requirements for work holding...mean that sometimes we will compromise or impact the design of that aerofoil, and most definitely impact the design of what we call the final fillet.' (Manufacturing Technology Interview 4)

These comments are two other examples of manufacturing geometry:-

'So we've had to put this 'sacrificial flange' on the shaft and then clamped and bolted around it and then sunk that into the machine rather than use that backspace for a collet device.' (Manufacturing Technology Interview 3, describing the addition of geometry to a component for workholding purposes).

'I guess from the manufacturing side of things, the way these components are manufactured is they're forged and then machined. So the aerofoil shape is actually forged with oversized blocks of metal in each end, then that part is clamped and the outer blocks are machined to give us the correct geometry which will then fit into the casing.' (Sub-system designer)

Definition: This code occurs when reference is made to additional geometry which needs to be added to the component geometry to facilitate the manufacturing process.
How to know when the theme occurs: Reference to added material. The interviewee will have a detailed knowledge of the manufacturing process. References to this code will typically be made by designers and manufacturing engineers involved in the detail design stages of the design process, therefore this geometry is 'hidden' from stage 1 preliminary.
Qualification: An in-depth discussion of the manufacturing process highlighting additional geometry to be added, typically for work holding.
An example of a situation where the code occurs:-
The geometry of the component is impacted by additional blocks which are added either side for work holding.

4.5.3 Category 2: Expressions of Manufacturing Impact

The first theme was a judgement of the impact of a manufacturing process on the size and shape of a component. The second theme is a consideration of how that manufacturing process can be expressed during the product introduction process.

Sub-category 2: Expression of impact - Empirical

Definition: occurs when there is evidence of experimentation in determining the impact of a manufacturing process on the size and shape of a component.
How to know when the theme occurs: the overriding factor in identifying this sub-theme is that the manufacturing process intended to produce the component will require some development work in order to meet the design requirements. The outcome of this work can be either successful or unsuccessful. Assessment of the process constraints on the product geometry will be from the results of experimental work or investigations.
Qualification: The theme will be qualified if the manufacturing process is a development of existing manufacturing technology, or the application of existing manufacturing technology to a new situation.
Disqualification: The theme will be disqualified if there is no consideration of the feasibility of the manufacturing process.
The following are situations where this theme occurs:--
Change of a bolted joint to a bonded joint.
The joining of two different materials which have not been previously joined using the specific process.
Change of the profile or shape of a component to improve its function, with considerations of how the manufacturing should take place.
The following is an example of a situation where this theme would not *occur:-*
The proposed manufacturing process is not feasible. A proven manufacturing process is used.

This example refers to the development of manufacturing technology and how differing project requirements feed a requirement to investigate process development:-

> '*Now what we're finding is that from one engine programme to the next, everything seems to change, so we don't seem to have a consistent joint thickness or a consistent material, so somebody will say to us, this seems very similar to this one we did before, either in this development programme or in this production phase. Yes, to look at it is very similar, but that's different, that's different and that's different, given our very limited knowledge, sorry guys, but we've now got to investigate everything again, because now we've got to develop it at that, that and that which have changed'* (Sub - system Design - manufacturing engineer)

Sub-category 2 : Expression of impact - Quantified

Definition: This code occurs when the manufacturing process constrains the size of the component to certain parameters. These parameters are expressed numerically.
How to know when the theme occurs: Reference to maximum or minimum allowed dimensions due to manufacturing. These dimensions are applicable to current manufacturing processes. These dimensional constraints can be seen across most components in the general arrangement. They will be considered routinely as part of the design process. The interviewee may or may not be aware of the manufacturing process which constrains the dimensions.

Qualification: Any constraint named must at least be described as 'due to manufacturing'. A description of the manufacturing process is a good qualifier, but is not essential.
Examples of situations where this code occurs:-
Minimum allowed wall thickness of a component *due to the casting process*.
Maximum *forging size allowed for bought-in component of finished material*.
Manufacturing maximums and minimums.
Examples of situations where this code does not occur:-
Minimum allowed component thickness.
Maximum casing size. (*reasons for maximum / minimum not given*).
This example illustrates the use of rules in the manufacturing assessment of a specific component and process.

> *'Right, so they take their fillet radius from there (structural and aerodynamic requirements) and then it would be a case of aligning it with the manufacturing, your manufacturing rules for fillets and the chordal geometry.'* (Manufacturing Technology interview 4)

Sub-category 2: Expression of impact - Standardised

Definition: this code occurs when component or component features are selected from a predetermined list of standard sizes. These standard sizes are fixed by the manufacturing process, or the supplier (and their manufacturing process).
How to know when this theme occurs: the interviewee will indicate that the component or feature is standardised. The interviewee may or may not know the details of the manufacturing process or reasons for the standardisation. One characteristic of this impact is there are rarely issues associated with it, as if the standardisation is accepted. Often the part will be bought-in and the standardisation will be defined by the supplier.
Qualification: The theme will be qualified if there is discussion of standardisation.
Disqualification: It will be disqualified if some parameterisation or customisation is allowed to the component.
Examples of situations where this theme occurs:-
'Standard range of pipes and fittings'.
'Use of a previous part as standard'.
Example of a situation where this themed does not *occur:-*
'We'll select an existing part from a previous assembly and modify the sizings'.

This example is from preliminary design and concerns a component known as the curvic coupling:-

> *'…at the beginning, you have the curvic there, so these are very expensive to make, or very expensive to produce the tooling to make, so you tend to pick one that's already been manufactured, so rather than optimising the radius to – you know – the nearest thou, you'll pick one from a previous engine and use that if you possibly can.'* (Preliminary Design interview 1)

4.5.4 Category 3: Knowledge Types

The final set of sub-themes demonstrates how the expression of impact is communicated throughout the product introduction process.

Sub-category 3: Knowledge Type – Structured

Definition: Examples of manufacturing engineering knowledge which can be expressed numerically, by algorithms or numerical rules. Information is generated and used during the design process. This information is repeatable across projects. They are documented in the form of parameters, dimensions, spreadsheet calculations or algorithms in expert systems. They can also be expressed graphically. Knowledge is said to be 'abstracted' – it is possible (although not always preferable) to apply it without fully appreciating the circumstances in which it was created. This is an example of explicit knowledge.
How to know when it occurs: Design requirements and/or information are expressed numerically. The format is stand-alone and can be repeatedly be used as a tool. Details of the manufacturing process which forms the knowledge may or may not be included.
Qualification: The theme is qualified if the knowledge can definitely be quantified and is document based.
Disqualification: It is disqualified if there is a degree of qualitative knowledge and/or if the knowledge is not documented.
Example of situations where the theme occurs:-
Manufacturing minimums and maximums.
Graphically-represented parameterised feature.
Example of a situation where the theme does not *occur:-*
Reference material (such as material properties) referred to, but not generated as part of the design process.

Example of a knowledge-based engineering system for linear friction welding:-

'And we also knew that to support that we need this blisk key system which is also where we recognised during the PD (product development) work that we needed to develop this blisk key system to support the vast number of iterations that we would need to be going through' (Manufacturing Technology interview 4)

An example of the importance of graphics in the communication process:-

'...the main deliverable of the designer is the solution drawing of the part.' (Sub-system designer)

This quotation is an example of structured knowledge created internally within the preliminary design department for assistance in managing the trade-off of design requirements:-

'One of the lads in the area, when he first joined he put together a guide for an engine. It's got certain criteria, you know, where you match certain parameters around the engine - performance and, as I said, it touches on the manufacturing things' (Preliminary design interview 4)

Sub-category 3: Knowledge type - semi-structured

Definition: Examples of manufacturing engineering knowledge which can be expressed quantitatively or qualitatively. They are referenced during the design process and support, but are not integral to the design process. The need to reference will depend on the situation, the context and the designer's own experience. They are documented in text documents. Knowledge is said to be 'embedded' – the designer needs to be able to browse and understand the context of the knowledge in order to be able to use it. Often the knowledge referenced is from outside the department. This is also an example of explicit knowledge because it is codified in text and numerics.
How to know when it occurs: Examples of numerical or descriptive information as seen in text documents.
Qualification: The theme is qualified if the knowledge is not documented as an abstracted rule or algorithm or graphical image.
Disqualification: The theme is disqualified if there is no documented evidence of the knowledge.
Examples of a situation where this theme occurs:-
An intranet website of material properties.
Descriptions of manufacturing processes.
Example of a situation where this theme does not *occur:-*
Conversational discussions.

Examples of semi-structured knowledge: minutes, emails, reports and presentations:-

'...the minutes – we're under a lot of time constraints, so the minutes tend to record the actions more often than the discussion. So it may not be possible to go back and find the particular conversation, merely the outcome.' (Manufacturing Technology Interview 3)

'I'm generally reliant on individuals copying the relevant people in on email communications.' (Manufacturing Technology interview 3)

Reports:-

'But there's also a DDR, which is the Design Definition Report, which you write which is basically a report that records why a design is how it is.' (Sub-system designer)

Presentations:-

(We're) *'trying to develop a one-page, simple foil that can be shown to seniors to say look, this is what we want to do with the technology, this is where we want to develop it'* (Sub-system design - manufacturing engineer)

Sub-category 3: Knowledge type – unstructured

Definition: Essentially, unstructured knowledge is the same as semi-structured knowledge. It is manufacturing engineering knowledge which can be expressed quantitatively or qualitatively, which is referenced during and supports the design process. Again, the need to reference will depend on the situation, the context and the designer's own experience. Knowledge is again 'embedded' – the designer needs to be able to browse and understand the context of the knowledge in order to be able to use it. Often the knowledge referenced is from outside the department. The difference lies in the media by which the knowledge is transferred. In this case, knowledge is not recorded and is communicated via social networks, hence the expert being questioned can supply some context. The theme can occur inside and outside the department, and be formal and informal communication methods. The current method of knowledge transfer is therefore tacit.
How to know when the theme occurs: the knowledge is communicated socially.
Qualification: The qualification of this theme is the manner in which it is communicated, i.e. socially. The content of semi-structured and unstructured knowledge is often similar, however the method of communication differs.
Examples of situations where this theme occurs:-
Discussions with people, group meetings.

Two examples which demonstrate the use of unstructured knowledge:-

'The guys from casting didn't like it but because of a different reason, because they didn't see any added value of the roadmap because they had all the information in their heads.' (Manufacturing Technology 2, technology roadmapping)

'We work on a slow turnover rate in this office. There always tend to be someone who knows what's happened before. I think if a whole new batch of guys were to come in and say we all went off elsewhere, then it's quite possible that they'd struggle, well not struggle, they wouldn't be able to get the same learning curve, if you like, as the people, as if the experience was in the vicinity. It's generally a matter of who do you ask? Who do I ask about this subject? And within half an hour you'll get a good understanding of what the issues are. Generally that's the way we work. It's not a knowledge-based system in that respect.' (Preliminary Design interview 2)

4.5.5 Examples of how the code was derived

The purpose of this section is to demonstrate how the coding was derived from the critical incidents listed. Two of the eighteen critical incidents have been selected as examples to illustrate this: a similar method was applied for all of the incidents.

An excerpt from each interview follows. The key areas of interest which were highlighted in the original text are shown in bold and numbered. Please note that some content has been changed for reasons of company sensitivity.

Example 1: Situation 6, from prelim design interview 2.

Key: Interviewer: I; Designer: D.

"I: What I'd like you to do is to think of a situation in your design role that you've encountered where manufacturing considerations have had some impact on the design. I'd like to know a bit about the situation, what the design requirements were that were affected, and why and what stage did this occur.

D: Yes, I saw your note that came round so I gave it some thought. I think ***the design of the HP compressor drum(1)*** *is the one I was going to discuss with you.*

I brought this picture along as well because it'll make it a little bit clearer. <Refers to drawing>. In the build shop – are you aware of the engine arrangement?

I: Well, I've been winging my way through the 'Introduction to Gas Turbines' course in the last few days on CBT, just to get up to speed with it, so I've got sort of a broad idea.

D: You know you've got three shafts – the LP, IP and HP? High pressure, intermediate and low pressure. So the HP – High Pressure compressor, is this unit here, that's the combustor and that's the turbine that drives it. Now this compressor drum is spinning at about 13000 rpm and carries six stages of blades on it…One of the ideas was to have the drum as one piece, which means we would weld the whole thing together, and you can see that these discs are already welded up anyway. ***The reason there's a bolted joint in the middle of the compressor is that we have what we call 'Material A' material at the back, and this front material is what we call 'Material B' (2,5).*** *They're both alloys of the same material, but they're dissimilar mixes.* ***This one, 'Material A', is a high temperature material(3,4)****, where the 'Material B' is a more – it's a good alloy, and it's very weldable.* ***The 'Material A' is highly unweldable, so to weld 'Material A' to itself, so we're going to weld there, and we've also got a weld there, to weld this drive arm to this disc we have what we call inertia bonding(2,6). So it's a new process(7),*** *and essentially requires you to spin one item, not very fast, but there's a massive flywheel, many tonnes of flywheel, energy on this, and we hold this disc stationary, spin one and jam them together and they bond together. Lot of energy involved, but it does give you a very clean bond, joint.* ***So we can do that, we can bond 'Material A' to 'Material A' and we do that there, and we do it there. But to bond 'Material A' to 'Material B' requires you to do some testing and a cost study. It's not to say that you can't do it - it's not proven technology(8). So the sub-system groups decided to get rid of our one-piece drum, in Prelim design we had a one piece drum here, with a weld at this point, and we said we'd like a one-piece drum… and as you can see now, they've got a bolted joint in there(10). That might seem immaterial, but it takes a long time to bolt these joints up and every time you do this you have to go through a balancing process. If***

it's proven that the drum is not quite as well aligned as it might be, you have to take it all off and remake the joint. And that's an incredibly long and expensive and time-wasting process(11). *So that's where we've been 'thwarted', in one particular case, by the manufacturing technology.*

I:…With the compressor drum, that means when it came to the information about the materials and the welding and the ins and outs of the manufacturing process, and the fact that it wouldn't work, where did you get the information from? What was the source of that?

D: ***…The experts there are the manufacturing engineers, and they have run the analysis and the tests on test pieces to say essentially what materials they've tried to bond together. So that's where we get the information about what materials we can match together and the quality of that bonded joint(12, 13). And I think there's an argument that says you can bond virtually anything to anything else, given enough time and effort in the manufacturing trials. But those manufacturing trials are very specific to the geometry in question. If we changed the diameter of this thing by 10%, we'd have to go through all the manufacturing trials again because it'll be different. We'd have a good guess at what it would be, but the actual end load and heat generated and that sort of thing is very specific to the geometry, so to do that you'd have to essentially run each one of these joints through manufacturing trials of the exact geometry. But the test pieces, which were specific sort of … bars, they gave the metallurgical information that we were after, that a good joint could be made. Well, I think they knew that anyway because any joints can be made. So it's not that you can't do it, it's not been proven(8)…That's where the expert knowledge is, there's literature on the subject, it can be useful but it tends to be a lot simpler to ask the people who know, go straight to the horse's mouth(12, 13,14).***"

The affected product is the HP compressor drum (1) which consists of six blade assembly stages which need to be assembled together. The method by which the assembly stages are joined depends on the material selection (2). The material selection is determined by the operating requirements of the particular blade assembly (3) and the material properties required to withstand this (4). In this specific case, this can lead to two scenarios: dissimilar materials are bolted (5) whereas like materials can be joined by the inertia welding process (6). The inertia welding process is in development (7) therefore its capability is still being developed and has not yet been proven for joining the two dissimilar materials (8). To do so would require additional cost and investment (9). This has been rejected by the next stage of the process (the operating business units) (10) due to the risk that this may concur on the design process (11). The interviewee has found out about the constraints of the process through discussions (12) with the manufacturing specialists who have been developing this process through trials and experimentation (13). They have found this to be a far easier source of specific and up-to-date knowledge than reading through literature on the subject (14).

From this narrative the categories were derived as follows:

Manufacturing impact: The interviewer is describing how the manufacturing process constrains a particular joining method selection for this scenario. Joining the two dissimilar materials is unproven. The interviewer knows the constraints, but not the detailed manufacturing reasons for these constraints. Consequently, this categorised as a Configuration Impact.

Expression of impact: How have these constraints been explained? Actually, the alternative proposed could work but it has not yet been proven or tested on that specific material combination. The results of experimental work have been discussed to prove this point but the process has not yet been developed to the stage where the process capability can definitely be quantified. Consequently this is an example of an Empirical Expression of Impact.

Knowledge type: The knowledge has been gained from discussions with the manufacturing specialists developing the process. It has been primarily verbal. Consequently this is an example of Unstructured Knowledge.

Example 2: situation 2 from prelim design interview 1

> *D: "**I think I was investigating a blade off design, on a casing(1,2). and so there are rules(4).** You basically have your blade off design and your pressure design and **manufacturing minimums(3)** and whole engine modelling loads and you just pick the thickest out of all those. We may have a Plum Folder on that**. We've got this 'Plum Folder' system you see. It's called 'Plum folders' because they're plum coloured(5)**. All our design rules are in there, which, to be honest, it does desperately need updating. But when you are doing a specific design you can look that up."*

The component is a casing (1) and the specific design situation is a blade off design (2). The casing must be able to contain a blade if it becomes detached from the main turbine assembly during flight (as the consequence of a bird strike, for example). There are a number of requirements which constrain the component sizings including minimum permissible dimensions obtainable from the manufacturing process(3). These are a known set of rules (4). These dimensional rules are stored in an official organisation document known as a plum folder (5).

The coding was again derived from the narrative as follows:

Manufacturing Impact: The interviewee describes how an unspecified manufacturing process constrains the achievable geometry for the component. As the manufacturing process is unspecified, this is another example of a Configuration Impact.

Expression of Impact: The constraints of the manufacturing process are expressed as a series of numerical rules. Consequently this is an example of a Quantified Expression of Impact.

Knowledge Type: the interviewee refers to an official organisational method of documentation for design rules. As the rules are numerical and are recorded in this way, the Plum Folder is an example of a Structured knowledge type.

4.5.6 Coding of Additional Comments

The six additional themes identified through the open coding of the additional comments were:-

a. Impact and knowledge types.

These were direct quotations associated with the categories and sub-categories discussed in sections 4.5.2 – 4.5.4 and were examples of each. Quotations typical to this category have been used in that section to illustrate examples of each category.

b. Business benefits.

These were quotations which supported and highlighted the benefits of better integration between manufacturing and preliminary design.

The majority of comments were concerned with the need to link the future engine strategy and future technology development strategies in the preliminary design department in a better, more formal way, earlier on. The benefits of this would be that preliminary design would have a greater awareness of the actual technologies available during preliminary design, and would be better able to influence the technologies being developed to be more in line with their requirements. There would be benefits for Manufacturing Technology in that they would have greater, more formal visibility of future requirements and be able to feedback their developments to influence those requirements. Much of the discussion was concerned with the Technology Roadmapping initiative which was under development within the Manufacturing Technology department at the time of the study and was in the process of being rolled out to engine projects. This initiative would address this issue. There was a consensus that needed to be addressed by both design and manufacturing collectively.

An example from the interview of when this has worked well is with specifying the number of blades in a blisk. The manufacturing process limits the permissible number of blades due to allowances for tooling clearances. In this case, the manufacturing technology team were able to due some initial calculations on the preferred number of blades prior to the stage 2 IPT launch. They found that they were able to remove two blades and this was communicated during the IPT launch.

The better integration of manufacturing and design at the early stages is primarily seen as a reduction of risk, as illustrated by this comment:-

"So there's a feeling overall I think that it would be nice to have a better visibility of what was on the horizon in a more formal way. Even if there was no money being spent, but just that you can understand at a level perhaps two or three engine requirements with a similar volume of inertia welding that we've seen on the [engine project]. But perhaps these new materials might be required, or it might be a requirement on this new component. Just so development programmes can be put in place early enough to de-risk those new engines. Because I don't think it's breaking great confidences or any sensitivities, it's just a better appreciation of company strategy, essentially." (Manufacturing Technology interview 3)

c. Size and shape drivers.

These quotations offered evidence that the method of manufacture influences the size and shape of the component and were used to develop the Manufacturing Impact sub-categories.

An example is given in this comment, referring to how geometry required to support the component during a joining process can compromise the design geometry:-

"So, the fact that we need that blade foot on there compromises that aerofoil hollowness. The fact that we need that foot on there compromises that fillet radius. To some extent, it could compromise the chord length. In terms of stagger as well, there is a maximum stagger that we can weld on so we could not have the blade staggered right round here, we just could not weld that with the machine that we've got." (Manufacturing Technology interview 4)

d. Commonality of purpose of design and manufacturing.

These quotations demonstrated that although strategic issues in communication were recognised and were being addressed (for example through Technology Roadmapping), there was a commonality of purpose across the groups involved in the different stages of the design process. All ultimately wanted to achieve the same outcome, particularly regarding future technology strategies.

"Historically, it appears that nobody has owned the process, for one reason or another. I'm working with Man Tech closely at the moment to try and develop a roadmap of what we are going to do with the technologies, trying to speak to the (business units) and (preliminary design) to see, what do we need to develop in the forthcoming years." (Sub-system design - Manufacturing Engineer)

e. Maturity of manufacturing impact

These quotations demonstrated a link between the expressions of impact used for a manufacturing process and a time-based view of the development of the process. The empirical impact of expression appeared to be used primarily for processes which were under development. Sometimes quantifiable rules could be expressed for known process parameters, other times it was clear that experimentation was required. This is discussed further in section 4.6.

> *"…although we had done some tests on some smaller diameter test pieces, to guide how well it bonded together, there was still some uncertainty in terms of what speeds and force was required to bond it together. So although we had a good idea, the inertia welding team still didn't feel comfortable committing to more than an extra ±x over the length of the component which, if you think about it, is still pretty accurate. But, on a similar component with a more established material, the tolerance was N ±0.25x, I think it was. So that gives you an idea of the difference it had. That was purely down to new material that hadn't been tested before. That's really where the uncertainty came from."* (Sub-system designer)

f. Knowledge sharing and use of knowledge types.

This category was primarily concerned with examples of the different knowledge type subcategories shown in section 4.5.4. The preferences and limitations for different knowledge types, and their importance in knowledge transfer, were also investigated. These are discussed further in section 4.6.

4.6 Key Observations

Having defined the data-driven codes through open and axial coding analysis, the final stage in the coding process was selective coding. There were two activities involved in this. The first was to examine and interpret the coding categories as a definition of the manufacturing knowledge requirements for preliminary design. This was achieved by reviewing the themes from the additional comments. It was found that these themes were related to the main categories derived from the analysis of the critical incidents. Consequently the themes were used to understand and interpret the main categories. Figure 4.2 illustrates the relationships between the main coding categories and the additional themes.

The second activity evolved from the first. As the meanings of each category were explored, relationships between them began to emerge. These relationships were represented as a conceptual framework of manufacturing knowledge for preliminary design.

Sections 4.6.1 – 4.6.3 discuss the meaning of each of the main categories. Section 4.6.4 explores the links between the main categories and presents and summarises the conceptual framework generated from this.

4.6.1 Category 1: the manufacturing impact

The optimum design outcome from preliminary design is a trade-off for a number of design requirements (Pahl and Beitz, 1988, p.2). This was clearly demonstrated by the interview data, particularly for preliminary design. For preliminary design in the collaborating company, the functional design requirements (performance, aerodynamics, stress, weight, noise, emissions, safety, etc.) are the main considerations during the design process, with perhaps performance being the most

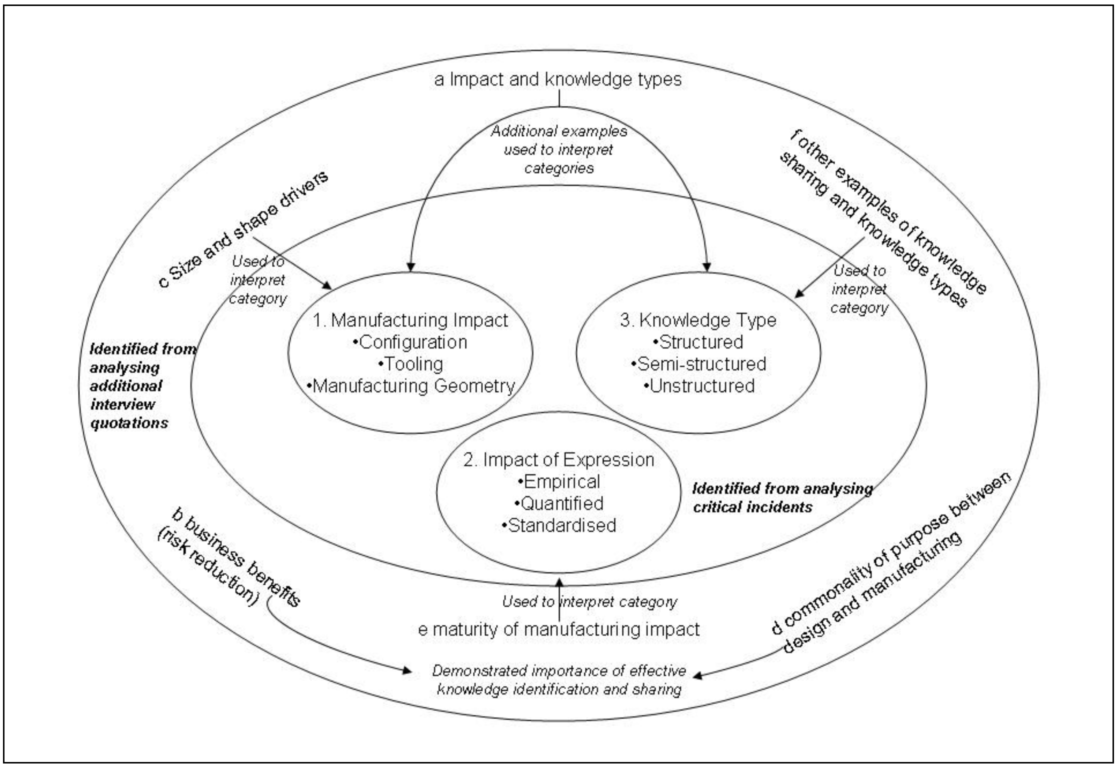


Figure 4.2 Summary of coding categories developed and their relationships

important because this needs to be satisfied or exceeded for the solution to be considered by the customer. Satisfaction of the functional requirements determines material selection for each of the components. The selected material then determines the options for manufacturing process selection. Therefore manufacturability is assessed indirectly as a consequence of other requirements. Historically manufacturing has been considered at this stage due to its impact on component cost. However, the feasibility of the manufacturing process fundamentally decides whether a component design is a realistic solution**.**

As seen in (Pahl and Beitz, 1988; Lovatt and Shercliff, 1998a; Chen, 1999; Nowack, 1997, Boothroyd et al., 2002), there is a relationship between the functional requirements, material selection, process selection and shape. This was also clear from the interview data.

In the analysis of this data, the selected method of manufacture was interpreted as creating a configuration envelope which places limitations on the size and shape of a component (the Manufacturing Impact). This method of manufacture may have a further effect on the material properties. The configuration envelope is specific to a particular method of manufacture and if more than one method is available, then the resulting configuration envelope may be different. This is shown in figure 4.3, which is an illustration of the manufacturing impact on a component. The original functional design requirements drive the component material selection which drives the manufacturing process selection. The configuration impact is shown by the differing configuration envelopes for processes A and B. The additional tooling impact and manufacturing geometry categories are additional process detailed process knowledge which drive the creation of the configuration envelope.

Two key findings were found from the analysis of the data. The first is the way in which a method of manufacture can have a positive effect on the configuration envelope of a component. Historically the manufacturing process has been viewed as a constraint or a limitation. During preliminary design method of manufacture has been inferred by selecting and modifying a previous component. The fact that the component was successfully produced infers that the manufacturing process is capable.

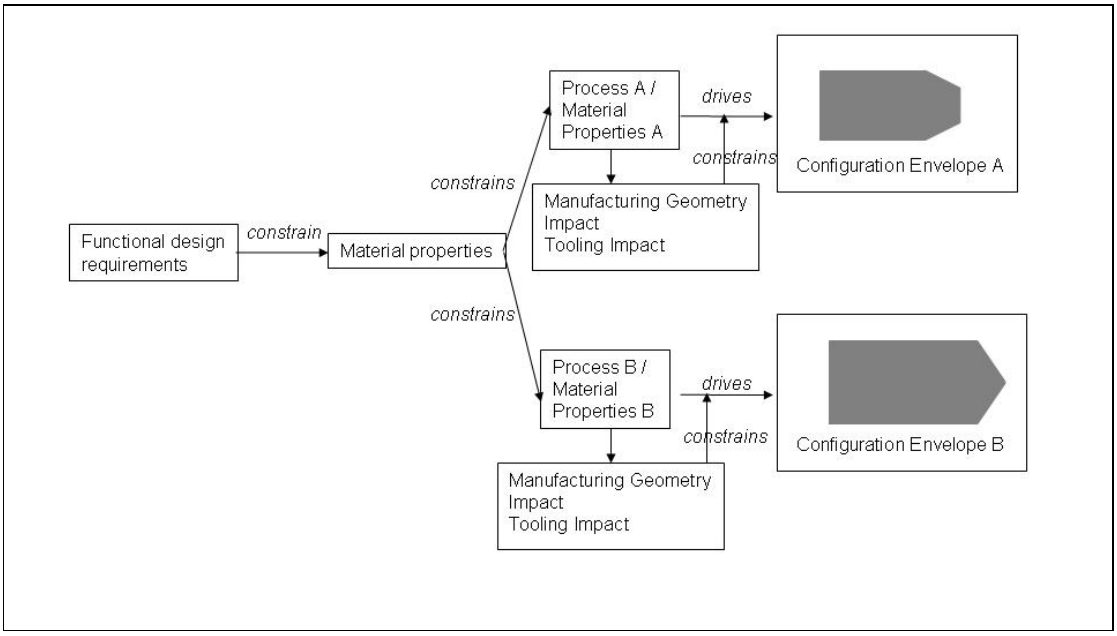


Figure 4.3: The impact of the manufacturing process on the component configuration

However, if new manufacturing technology becomes available, the scope of what can be achieved in terms of size and shape is directly altered, leading to new creative possibilities and a new potential configuration envelope. An example of this given in the interviews was the creation of the blisk component to replace the conventional blade and disk assembly. The conventional assembly features for the blade and disks were no longer required, giving weight and stress advantages. This development was made possible by developments in a joining method called linear friction welding.

The second key finding is the extent to which the manufacturing impact is defined at specific stages of design. It has been demonstrated that knowledge of the configuration envelope boundaries alone has been used in preliminary design, as seen by instances of the configuration impact. It is only at subsequent, more detailed stages of the design process that the reasons for these configuration boundaries are explored. The results of this can be seen in the descriptions of the tooling impact and the geometric impact. In the case of the geometric impact, where additional material geometry needs to be added for work holding purposes, this impact can literally be 'hidden' and the preliminary designers not aware of the situation.

This suggests that in order to successfully communicate details of the manufacturing impact to preliminary design, a degree of abstraction of the knowledge must take place between the detail design / manufacturing engineering domain in order for this knowledge to be effectively used. The preliminary design view of the configuration envelope can be seen in figure 4.4, where the degree of abstraction referred to in the literature during preliminary design can therefore be illustrated by this impact on the geometry.

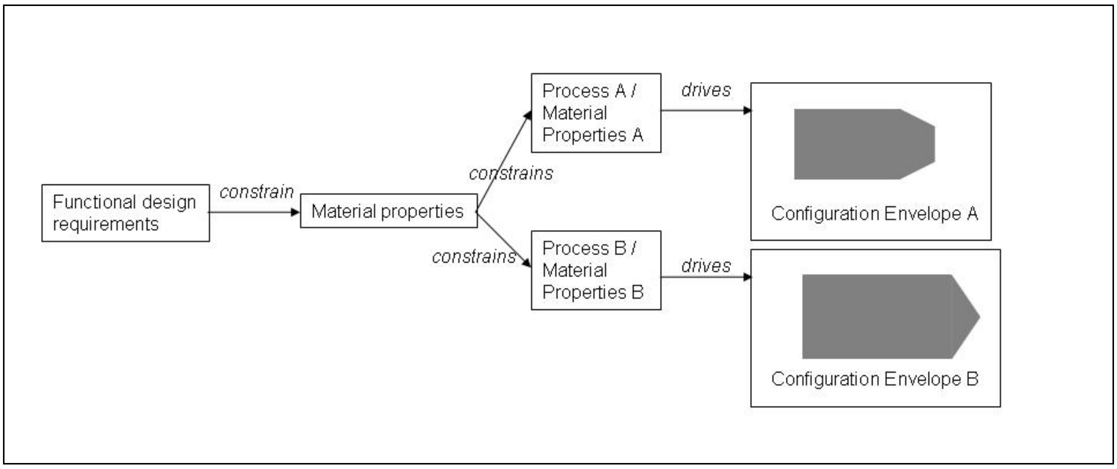


Figure 4.4: Impact of the manufacturing process on the component configuration from the perspective of preliminary design

4.6.2 Category 2: the expression of impact

The key finding for this impact is that the three expressions – empirical, quantified and standardised - refer to the level of maturity in the knowledge supplied, in line with the research by Bohn (Bohn, 1994). The empirical expression of impact is most frequently seen when a manufacturing process is in development. At this point, the manufacturing specialists are seeking to increase their level of understanding of the capability of the manufacturing process. Once a particular level of understanding is achieved, then the limitations of the process – and its effects on the configuration boundary – can be expressed in a quantified way. As development again continues and knowledge is increased, the manufacturing specialists are finally able to specify the configuration boundaries according to repeatable pre-determined process capability requirements. The impacts are therefore expressed in a standardised way.

Consequently, the requirements for particular expressions of impact can be linked to the maturity of the manufacturing process, as illustrated in figure 4.5. An indication of process maturity emerged from the interviews as an addition to the existing requirements of method of manufacture, process capability and cost (Pahl and Beitz, 1988; Balogun et al., 2004).

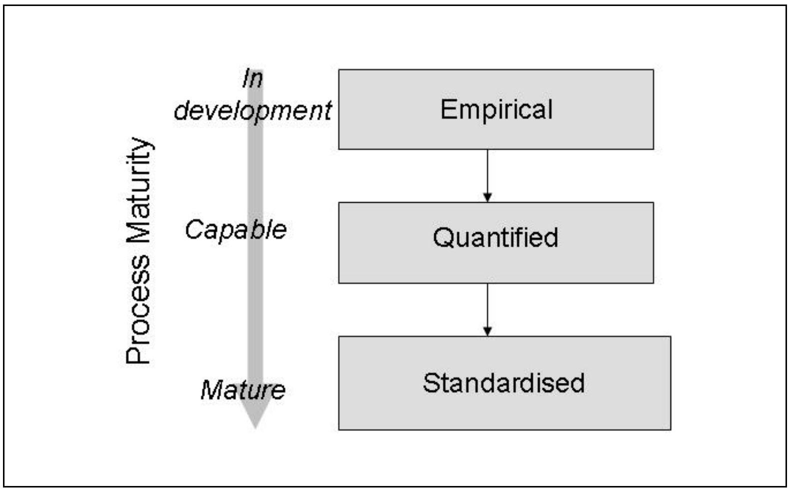


Figure 4.5: Maturity of manufacturing process and expressions of impact

4.6.3 Category 3: the knowledge types

This final category explores the combination of methods by which the expressions of impact can be communicated. It is proposed that the definitions of 'structured' and 'semi-structured' knowledge conform to existing definitions of knowledge as being 'explicit' or 'codified'. The definition of 'unstructured' knowledge correlates with the definition of 'tacit' or 'personalised' knowledge (Nonaka, 1994; McMahon et al., 2004). In the interviews, a number of opinions were raised on the validity and use of the different knowledge types. From the data, the advantages and disadvantages of the different knowledge types follow.

Structured

The strength of structured knowledge is the extent to, ease with and speed with which it can be re-used. For example, once a spreadsheet of performance values is compiled, the effect of different design configurations can be updated almost instantly.

Two major disadvantages of structured knowledge were highlighted in the data. The first is the effort required to reach the situation where knowledge can be captured and abstracted in this way. The second disadvantage is the effort required to actually capture, effectively store the knowledge and to keep it updated. The abstraction of structured knowledge, that is, its separation from its context creates two risks. The first is that the knowledge may be used wrongly because the user does not know the circumstances in which it has been created (i.e. a standard bolt may be used for the wrong type of joint). The second is that structured knowledge may be used for many years when it is actually out of date (standard tolerances, for example).

The adaptive design environment does not give many opportunities for direct knowledge reuse, particularly where new process developments are taking place:

"…whilst when we do a new engine this technology's from a previous one and this one's from a previous one, this isn't, these aren't, that probably isn't that much like the other one…" (Preliminary Design interview 4)

However, there appears to be a need to attempt to define and communicate knowledge in a structured way, perhaps because results can be generated and interpreted quickly and easily:

'*What designers can't do brilliantly is design to meet a cost, a weight target. I can do this, and this is what happens. I could do this, and this is what happens. But it keeps bouncing numbers at me. And I'd probably want to work to something like this (spreadsheet shown cost comparison of changing a number of parameters), where you work up to an overall thing.'* (Preliminary Design interview 4)

Semi-structured

Semi-structured knowledge is useful in that it can supply the context which is not present in structured knowledge. Because it requires less precise definition when compared to structured knowledge, it can be compiled more quickly and more comprehensively. However, the sheer volume of information available can affect the feasibility of capturing it in its entirety. A large amount of documentation can be generated which may be difficult to interpret and search, especially if the knowledge is not so well organized. The user therefore needs to be aware of the context of the knowledge before their search. In the case where the user is looking to improve their knowledge of a particular subject, it may be difficult for them to define the context. Even if the user is aware of the context, they may find that the level or content of knowledge contained in the document is insufficient for their requirements.

An additional limitation is the effort required in keeping the knowledge content up to date, which may well be a more cumbersome task than that for structured knowledge. As a consequence, mistrust in the recorded knowledge and its accuracy may be expressed. This was certainly the case in the interviews. That said, semi-structured knowledge remains useful for documenting complex situations and reasons which cannot be expressed by structured knowledge alone.

'It gives you an insight into the way they approach things, which is very useful, often, if you don't know how or why something's been designed in a certain way. It doesn't really help you to apply that component or assembly in another situation…' (Preliminary Design interview 3)

Unstructured

Reasons for the use of unstructured knowledge varied. Asking an expert in a different specialist area may supply the context which is missing in searching for semi-structured information. In the interviews, trust played an important part in determining the accuracy of knowledge, with people often being trusted more than documentation:

'Certainly, in accessing information there are reports, but particularly the view of manufacturing that I guess you're looking at in more detail – purely by talking to people, because they've got the best experience and the best knowledge of how the process works.'(Sub-system designer).

Other reasons cited for using unstructured knowledge were because the knowledge did not exist in any other format, to communicate sensitive knowledge which they did not want to record and personal preference.

The form of unstructured knowledge used most often by those involved in the later detail design stages was via the formalised social network of the IPT (integrated project team). For the preliminary designers, social networking was also of great importance, however their involvement in IPTs was not so evident (typically IPTs were formed at the next stage of the design process) and they had greater reliance on informal social networks. The limitations in this are the validity and strength of the social networks.

4.6.4 Development of a conceptual framework

The three main categories are inter-related, with each describing a particular element of manufacturing knowledge for preliminary design. The manufacturing impact depicts the knowledge of manufacturing required during preliminary design as an impact on the component configuration. For the preliminary stage this impact is demonstrated by the constraints on the component configuration. The detailed manufacturing knowledge to give the reasons for this impact becomes more evident in later stages of the design process.

If the manufacturing impact identifies the configuration envelope for a component and the resulting configuration boundaries which may result, then the expression of impact demonstrates how knowledge about the configuration boundaries may be communicated. The analysis of the data showed a one-to-one relationship between the manufacturing impact and the expression of the impact.

This expression of impact can be expressed in one of three ways depending on the maturity of the manufacturing process. If the process is in development then the expression of impact will be empirical, based on experimentation and expert opinion. If developments have progressed to the stage where some rules can be applied then the expression of impact will be quantified. Finally, if process capability has been established within desirable limits then the component standardisation may be acquired.

The three different knowledge types can be used to communicate the different expressions of impact. This is a one-to-many relationship: more than one knowledge type can be used for one expression of impact. No preferences for specific knowledge types for particular expressions of impacts were apparent except for the standardised examples, where the knowledge type was primarily structured (table 4.6). Consequently the advantages and disadvantages of the knowledge types could highlight the strength of their use at various stages of process maturity.

Table 4.6: Expressions of Impact and different Knowledge Types

	Knowledge type		
Expression of manufacturing impact	Structured	Semi-structured	Unstructured
Empirical	Manufacturing process for bearing support structure assessed. A series of weight / cost calculations were carried out and recorded on a spreadsheet to find the optimal solution.	Investigation into using inertia-welding to replace bolted joints for two stages of the HP compressor drum. Results of investigations reported via email.	Investigation into using inertia-welding to replace bolted joints for two stages of the HP compressor drum. Results of investigations discussed in IPT meetings
Quantified	Assessment of geometry for casing thickness. Three scenarios were calculated using formulae (blade-off design, pressure design, whole engine modelling loads, manufacturing minimums) and the thickest dimension taken as the design case.	Assessment of chordal geometry for the blade: the results of the calculations are documented in IPT meeting minutes.	Assessment of chordal geometry for the blade: the calculated results are discussed with designers (either in IPT meeting, or offline).
	The chordal geometry of a blade which is linear friction welded is optimised in a key system.	No examples recorded.	No examples recorded.
Standardised	IP fixed vanes, shrouds and blades have manufacturing are forged with added blocks for work holding later on in the process. The designers try to use the same block sizings (from previous drawings) to standardise work holding.		

Below are some examples from the interviews of different knowledge types being used for different expressions of impacts:

- Rules (Quantifiable impact) being used in a key system (structured knowledge) within a department to assess the number of blades required in a blisk. The results of these rules communicated via meetings (unstructured knowledge), reports and a comms sheet (semi-structured knowledge).
- Successive experiments (empirical impact) being carried out for inertia welding until rules (quantifiable impact) can be derived. Results being communicated via email (semi-structured knowledge) and discussion (unstructured knowledge). Eventual rules captured in a spreadsheet (structured knowledge).
- A designer preferring to talk to an inertia welding expert (unstructured knowledge) to assess the effect of the technique on component geometry (empirical impact) in preference to a website (semi-structured knowledge).
- A novice designer preferring to talk to experienced designers for learning (unstructured knowledge), but expressing a preference using a key system to optimise component geometry (structured knowledge).

The relationship between the three categories can be summarised and illustrated by a conceptual framework, as seen in figure 4.6. The manufacturing impact – the effect on the overall configuration of the component – may be expressed as being empirical, quantified or standardised. The suitability of the expression of impact will depend on the maturity of the manufacturing process. This can be shown using structured, unstructured or semi-structured knowledge, with possibly more than one type being required simultaneously.

This conceptual framework represents a hypothesis of the manufacturing knowledge during the preliminary design stage of complex mechanical components. It demonstrates that during the preliminary design stage the manufacturing process knowledge is directly related to the impact on the component configuration. The maturity of this process is also an important factor, as is having a range of tacit and explicit elements with which to transfer and document it.

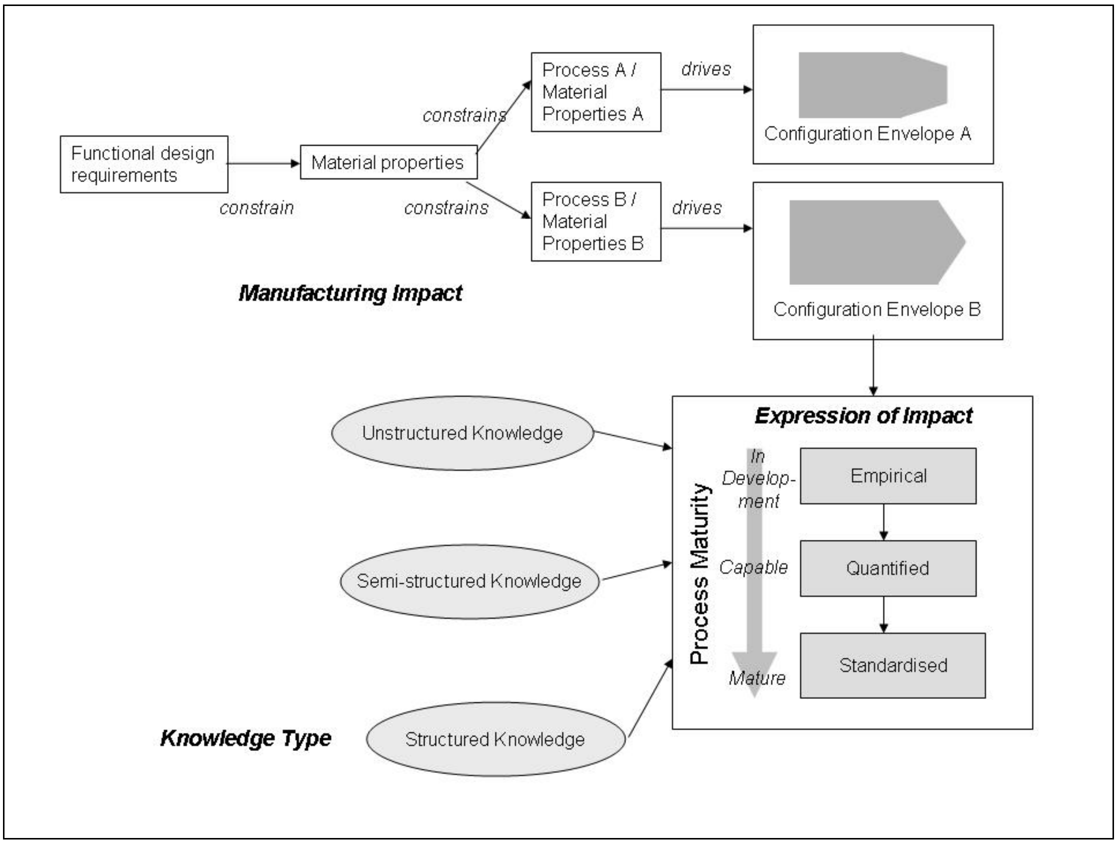


Figure 4.6: A conceptual framework of manufacturing knowledge in preliminary design

Table 4.5 gives examples of the manufacturing impact for different components at different stages of development. Where it has a positive effect, the development of either an existing or new manufacturing process has created an opportunity to either better manage the trade-off or even improve the functional design requirements. The impact of expression for this situation tends to be empirical, indicating that the development work is taking place. At the opposite end of the spectrum, the manufacturing impact is seen as a constraint on the functional requirements. At this point the expression tends to be quantified or standardised, indicating a mature manufacturing process. There may be little incentive to develop the manufacturing process in this case. This may because there would be little benefit in the cost of manufacture to do so, alternatively it could mean that the component is being produced to the desired process capability. It can therefore be seen that a new product will be composed of a series of components at different stages of development. Some components may be undergoing development and hence be changing their configuration envelope. Others may be legacy components which are re-used in successive engine projects. These are in line with Pahl and Beitz' categories of adaptive and variant design respectively (Pahl and Beitz, 1988).

The extent to which a new product is composed of components under development and legacy components must therefore be considered when assessing risk for new product introduction. Although out of scope of this study, it is noted that the organisation has strategies to deal with this situation. It tends to be governed by project budget and lead time. Consequently some initial risk mitigation takes place as the project commences, with contingency funding and time built into the project plan.

The components undergoing development work regarding manufacturing processes stand out as a case worthy of further exploration. The way in which the manufacturing process knowledge (and its maturity) needs to be compiled is of particular interest and important in mitigating the risk.

4.6.5 Effect on product sub system

As discussed in section 3, the scope of this study is concerned with the impact of an innovative manufacturing process at component level. However, it is important to acknowledge change propagation: that the change may have an impact on other components both within the immediate assembly and sub systems (Eckhert et al., 2004; Flanagan et al., 2003).

The change in component configuration in this study is due to change caused by a development in the manufacturing technology. Eckhert et al (2004) categorise this change as an innovation, which is a type of initiated change because such changes arise as a consequence of customer requirements, which are either known at the start of a design project or during the design process.

Figure 4.7 illustrates the effect of a change in the configuration envelope due to the manufacturing impact. Here, two components X and Y are shown which are part of the same sub-system and have the same functional requirements. Component X has had a change to the configuration envelope as a consequence of developing the manufacturing process. Component Y is a legacy component with no changes. The changes to the configuration envelope for component X affect the sub system in two ways. Firstly, there is a change in the functional requirements. This may affect the configuration envelope for component Y. Secondly, the configuration change itself impacts on component Y. Consequently, although component Y had been a legacy component, there may be a possibility of further developments to this component which would need to be assessed.

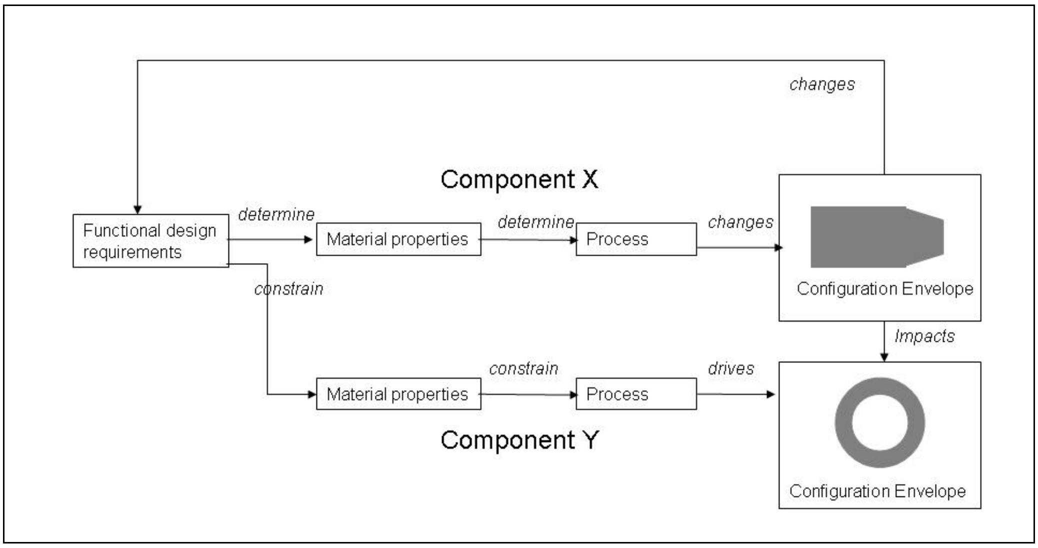


Figure 4.7: Effect of the manufacturing impact on sub system

For the purpose of this work, it is assumed that the change to the configuration envelope as a consequence of the manufacturing impact is managed through subsequent analysis work. Therefore the risk is concerned with the readiness of the manufacturing technology.

4.7 Summary

An exploratory study was undertaken into the nature of manufacturing knowledge for preliminary design. The objective of the study was to address the research gaps identified in the literature by seeking a better understanding of the impact of manufacturing on the preliminary design stage and how this can determine the requirements for manufacturing knowledge at this stage.

A series of semi-structured interviews were carried out with design and manufacturing specialists concerned with the preliminary stage of the design process to collect data for analysis. The analysis was data-driven, seeking to identify a number of key themes from the data. Grounded theory coding techniques were used to define three main categories, each of which could be described in more detail by three sub-categories.

Three main categories emerged from the data: the manufacturing impact which describes how the method of manufacture ultimately impacts on the configuration of the component; the expression of impact, which describes the knowledge about the configuration boundaries as being derived empirically, quantified or standardised and finally the knowledge types which can be used to communicate the expression of impact. These three categories can be related together as a conceptual framework which forms a hypothesis for the requirements for manufacturing knowledge during preliminary design.

In addition the analysis uncovered the following key findings:-

1. The impact of manufacturing is represented by its impact on the configuration envelope during preliminary design; at later stages of the design process the reasons for those impacts are detailed and considered.

2. It is important for manufacturing processes in development to be considered during the preliminary design process, because this can change the configuration envelope in such a way to have a positive effect on what can be achieved in terms of the functional design requirements.

3. The expressions of impact used to describe the manufacturing impact vary according to the maturity of the manufacturing process being considered. Consequently the empirical impact of expression is useful when considering a manufacturing process under development.

By constructing the conceptual framework, manufacturing knowledge for preliminary design was identified, together with mechanisms for sharing it. However, the concept framework was an abstract view of the requirements which required further detailed investigation. As the maturity of the manufacturing process had also emerged as a key area of interest, further investigation was again required to explore this observation in more detail. A further investigation into acquiring detailed innovative manufacturing knowledge would also enable a validation of the conceptual framework.

Chapter 5

Investigation into Manufacturing Knowledge for Blisks: a Detailed Study

5.1 Introduction

The first data collection activity (chapter 4) investigated the nature of manufacturing knowledge used in preliminary design for complex mechanical components. The output of this activity was a conceptual framework which gave an abstract view of the knowledge requirements and also the types of knowledge which should be used to depict them. Combinations of knowledge types were required depending on the maturity of the manufacturing process being investigated. This activity identified the manufacturing knowledge requirements for preliminary design.

The decision was taken to undertake a second, more detailed study to follow on from the first data collection. The objective of this study was to develop a more detailed understanding of the manufacturing knowledge requirements and how they were acquired and shared within the preliminary design process. This was with a view to the future development of a systematic methodology. The decision was taken to focus on a narrow case where the requirements could be investigated extensively. A suitable subject for this activity would highlight and further develop the main findings from the first study. It would be a complex mechanical component with more than one method of manufacture, with at least one of these methods being in development.

This second study also developed the themes which emerged from the previous study, focussing on identifying examples of manufacturing impacts, expressions of impact and knowledge types. Having identified examples of these at a general level in the first activity, examples of each could be explored in more depth to see how they applied to the situations which would be encountered during the preliminary design process. Consequently this detailed data collection activity would also be an initial validation of the conceptual framework.

This chapter discusses this second data collection activity which addresses research objective 2 and begins to address research objective 3. There were two parts to this data collection. The first was a ‘requirements capture’ exercise in which the manufacturing knowledge requirements relating to a specific component were identified and collated from various sources within the organisation. This exercise identified three things: the technical knowledge required, the rationale for that technical knowledge and knowledge sharing issues which arose from the identification of the knowledge. The manufacturing knowledge collected was also analysed according the code developed in chapter 4. The second part of the activity concentrated how this knowledge had been acquired by identifying the knowledge flow and rationale during the data collection, resulting in a study of the interaction between different specialist domains.

This activity took place over a period of six months. The first three months were concerned with gathering and verifying the knowledge requirements collated and the second three months with analysing and organising the knowledge requirements.

5.2 The Requirements Capture Exercise

5.2.1 Component selection

The objective of the requirements capture exercise was to investigate a specific component in detail and its manufacturing impacts, thus continuing to develop the notable findings from the first data collection. A suitable component would therefore meet the following criteria:-

1. The component would be an important consideration during the preliminary design process.
2. The component would have more than one method of manufacture in order to make a comparison (and therefore have more than one potential configuration envelope).
3. At least one method of manufacture would be a new method in development (therefore expressions of impact would vary).

Such a component could therefore be considered as a purposeful sample because it would be deliberately selected to exhibit these criteria.

The component selected from the collaborating company for investigation was the blisk, a component specific to the design of gas turbine engines. This component had been highlighted during the first data collection as being of particular importance during preliminary design. The name is derived as a shortened term for a 'bladed disk'. The conventional compressor assembly is a disk into which a number of blades are manually slotted during assembly. Both the disk and blades have a series of complex assembly features to enable this manual assembly to take place. These add weight at the core of the disc which affects the rotational speed of the compressor, its operating temperature and consequently the performance of the engine. The methods of manufacture involved in the conventional compressor assembly are primarily forging for the disk and a proprietary casting process for the blades.

A considerable performance improvement can be gained by treating the disc / blade assembly as a single component – the blisk. This results in a weight saving at the core as the assembly features are no longer required. An illustration of a blisk is shown in figure 5.1.

For small diameter blisks, the component can be machined from solid (MFS). However, as the diameter increases the economic viability of this solution decreases.

An alternative is to join blades to a disc using a joining technique known as linear friction welding (LFW). This again removes the need for the assembly features and results in a weight advantage. Of the two methods of manufacturing considered, machining from solid is the more established and mature process. At the time of the research, the linear friction welding process had been historically applied to military projects. A substantial amount of development work had resulted in a technology transfer to civil projects.

The organisation has and is continuing to develop expertise in both processes. For machining, this expertise is spread amongst a number of manufacturing engineers based in the sub-system design departments for both processes. For linear friction welding, there is a tool design and process development team in the sub-system design department. There is also a process development team based in the Manufacturing Technology team (an organisation-wide research department) which works closely with the sub-system team.

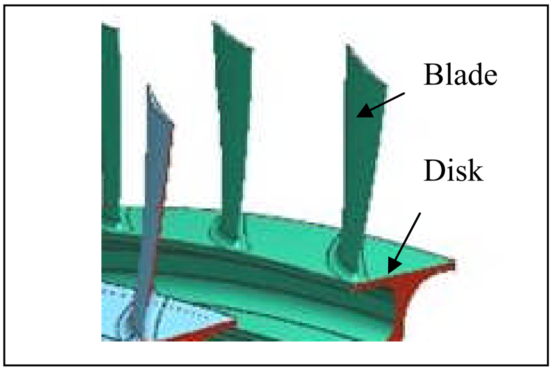


Figure 5.1: Example of a blisk assembly (reproduced with permission from Rolls-Royce plc)

5.2.2 Research design and techniques

For the requirements capture exercise, the knowledge requirements which would be relevant at the preliminary design stage for both manufacturing processes were to be collated. In selecting a suitable research technique, there were four considerations:-

1. The knowledge level and detail of the knowledge.

The first data collection activity was designed to investigate the nature of manufacturing knowledge rather than detailed examples of knowledge requirements. Therefore the focus of data collection for this second activity moved from the general to the more specific and detailed. It was important that the research techniques adopted would be flexible enough to collate and organise the knowledge requirements adequately.

2. Sources of knowledge and the identification of these.

A relatively small number of people within the organisation were involved in the design and manufacturing assessment of this component. It was important to ensure that they were correctly identified and able to contribute to the requirements capture activity. Further exploration of the job roles associated with the component and process were therefore required to identify suitable sources (people and documents) of the knowledge.

3. The author's own experience of the component and processes.

For the first data collection the author was able to draw on their own general knowledge of design and manufacturing engineering within an aerospace context. This second activity involved the collection of specialist process and component knowledge which was outside the scope of the author's own knowledge. This would therefore again require an exploratory approach, however validation from the process experts would be of high importance to verify the requirements captured.

4. Other knowledge perspectives which may be required.

The research technique selected would also need to be flexible in order to capture any other perspectives of the requirements capture, such as the knowledge rationale or any notable experiences in knowledge sharing.

The technique selected for the data collection was again face-to-face interviews with design and manufacturing engineers within the organisation. However, for this activity the approach adopted was more unstructured than the first set of interviews with a flexible set of topics for discussion. Each interview was initially arranged around the topic of blisk design and manufacture requirements, with a view to creating a manufacturing advisory system. The actual topics discussed were then tailored to the specific interviewee, often being generated by the interviewee themselves. This flexibility was deliberately used to enable the capture of both the technical requirements and also the rationale and additional knowledge sharing requirements from the point of view of each interviewee. Informal notes were taken for each interview. An overview of the topics discussed for each interview is shown in section 5.2.4.

The activity was designed to achieve research validity and reduce bias in the following ways:-

1. By peer feedback. Following each initial discussion a follow-up session took place with each individual interviewee to check the author's understanding and accuracy of the data collected.

2. By data triangulation. Two methods of data triangulation were employed in this activity. The first was by collecting the data from a number of different sources within the organisation. For the linear friction welding process, an additional document source was used to compare the data collected in the interviews with that recorded.

This was an internal technical report, published in 2001, which documented each stage of the linear friction welding process in detail.

5.2.3 Identification of knowledge sources

A comprehensive view of the manufacturing knowledge requirements needed to assess the blisk during preliminary design was required. From discussions about the informal and formal social networking for knowledge sharing identified during the first set of interviews, it was recognised that this knowledge often existed outside the preliminary design department and was sourced by them during the design process. Consequently it was important to identify these main sources, where they were placed within the organisation and their role in the design process. This was achieved by applying the informal social network. Potential candidates were identified from discussions with the interviewees from the first set of interviews and department colleagues. Two of the candidates had been interviewed during the first data collection activity and they were able to identify other relevant people, usually people with whom they had worked or consulted on current and previous engine projects. These were design or manufacturing engineers from the sub-system design teams, or specialist manufacturing technologists who would be involved in the manufacturing process assessment. A total of four main contacts and two additional contacts were established. Each contact was concerned with a particular aspect of the component and process assessment and became involved at varying stages of the design process. Each of these contacts is therefore considered to have a specific domain of knowledge and be a specialist in that domain. The contacts are summarised in table 5.1. The actual names and details of the interviewees have remained anonymous in order to avoid identification, however they are placed according to their particular domain specialism. As with the first data collection activity, the interviewee's details were not considered to be significant because the focus was on identifying the manufacturing knowledge itself.

5.2.4 Running the data collection activity

There were two interviews with each domain – one to gather knowledge and the second as a follow-up to verify the knowledge collected. Each discussion took around one and a half hours. Notes were recorded by the interviewer and written up afterwards. Below is a summary of each first, main interview and the discussion topics which featured.

1. Interviewees: 4 (Manufacturing technologist for LFW), 5 (Tool designer for LFW) and 6 (Manufacturing Engineer for LFW).
This took place as a group discussion rather than individual interviews. The main consideration for the meeting was the development of a manufacturing advisory system and the LFW manufacturing knowledge which would be required for this: identification of manufacturing concerns, parameters, dimensions and constraints which would be required for an initial manufacturing assessment. These were then compared to the tool design report.

2. Interviewee: 1(Preliminary Mechanical Designer)
Topics considered were: the ‘configuration envelope’ of the blisk – its functional requirements, how component sizing affects this, how the manufacturing process affects the component sizing and resulting effects on other components in the general arrangement; specific concerns about methods of manufacture and the trade off between selection; the knowledge required to make an initial assessment. The findings from interview 1 were also considered and compared to preliminary design requirements.

Table 5.1: Summary of contacts for data collection activity

Contact	Department	Specialist domain	Range of knowledge
Main Contacts			
1. Preliminary mechanical designer	Concept / Preliminary design (whole engine)	Preliminary mechanical (whole) engine design (Stages 0 – 1 of organisational design process).	Knowledge of the component (in terms of overall system architecture), overall understanding of some of the (mainly historical) manufacturing processes.
2. Designer	Sub-system design	Initial blisk manufacturing assessment (Stages 1-2 of organisational design process)	Detailed knowledge of the component, a more detailed understanding of the manufacturing processes available (current, historical and future) and factors influencing decisions for their use.
3. Manufacturing Technologist	Manufacturing Technology	Manufacturing specialist – machining from solid (MFS) (Stages 1 – 2 of organisational design process).	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.
4. Manufacturing Technologist	Manufacturing Technology	Joining specialist – linear friction welding (LFW) (stages 1 – 2 of organisational design process)	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.
Secondary Contacts			
5. Tool designer, LFW	Sub-system design	Specialist in tool design for LFW process.	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.
6. Manufacturing Engineer, LFW	Sub-system design	Specialist in LFW process.	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.

3. Interviewee: 2 (Designer)
The topics discussed were the design issues with the blisk component and the resulting effects on manufacturing; manufacturing considerations for the blisk and different method of manufacture options. There were also some discussions about the design process, the type of assessment work being carried out during the process and recent changes and initiatives which had been put into place to improve this.

4. Interviewee: 4. (Manufacturing Technologist, MFS)
The main topic discussed was the important manufacturing knowledge relating to MFS and cost models which had been created based on that knowledge.

5.2.5 Data analysis

Initially, the knowledge requirements were extracted from the interview notes and listed for each interview for comparison. These were then verified during the second follow-up discussion.

The requirements for each interview were analysed and categorised according to the type of manufacturing impact and expression of impact as derived in chapter 4. The potential knowledge types used in each case were also considered. This initial analysis led to some conclusions about the knowledge requirements and their rationale. The results are presented in section 5.3 and discussed in section 5.4.

5.3 Results

A summary of the manufacturing knowledge requirements is shown in table 5.2 and is categorised according to manufacturing impact, expression of impact and knowledge types. The requirements recorded for each domain are also shown separately.

5.4 Key Observations

Three key observations emerged from the results. These were the differences between the different domains, the categorisation of the knowledge according to the developed code and the resulting apparent existence of a gap in the design process. These are discussed in turn.

5.4.1 Differences in knowledge requirements between domains

Although the initial aim of the interviews had been to consider knowledge for a manufacturing advisory system, it became clear during the review of the interviews that there were differences in the manufacturing requirements from the perspective of each domain. Consequently the focus was not on knowledge identification as such, but on how the knowledge was acquired and shared according to the requirements of each domain. This is illustrated by figure 5.2.

The requirements for preliminary design first appeared to be a reply to a simple yes / no question, *'Can the design be manufactured?'* with the intention of creating a master list of technical knowledge requirements for each process. However, as can be seen by the differing responses in table 5.2, a significant amount of analysis is required 'downstream' from preliminary design in order to answer this question. This is shown by the differences in knowledge requirements for each domain. For each domain, the following was deduced:

Table 5.2: Manufacturing knowledge requirements for preliminary design captured through informal discussion

Domain	Requirements	Coding
Preliminary whole engine design	Can we make it? Is blisk to be manufacturing by LFW or machining from solid?	Configuration impact, Empirical expression of impact, All knowledge types
Initial blisk manufacturing assessment	1. Dimensional limitations of lfw and machined blisks, i.e. the convention is that smaller blisks are machined. What are the dimensional limitations? 2. Need to assess specific dimensions associated with the blisk geometry to ascertain feasibility*. 3. Potential repair strategy 4. Total blade replacement capability 5.Component lifecycle cost	Tooling impact. Quantified impact of expression as it is a known convention. All knowledge types. Dimensions show the Tooling Impact. Expressions of impact are empirical. All knowledge types are used. In some cases the dimension has a rule associated with it so it is a standardised expression of impact with a structured knowledge type. Other (in service) Other (in service) Other (costing)
LFW manufacturing assessment (meetings and discussions)	1. Existing LFW machines are assessed to see if they can accommodate the component. Again a number of specific dimensions are assessed relating to the component geometry*.	Tooling Impact, empirical, all knowledge types. Empirical, structured.
LFW manufacturing assessment (tool design report)	1. Assessment of component fit to existing machines. Again, specific component geometry is required to assess this*. There is more detail in the report than in the previous example of the meetings and discussions. 2. Assessment of LFW geometry boundary conditions, process parameters and machine capability limits.to assess fit in machine. Again, specific detailed component geometry is required to assess this and compared to specific machine tool geometry and capability*. 3. Assessment of design feasibility. Uses a series of scoping calculations to investigate forces and stresses involved in the process*. 4. Manufacturing Targets: 5. Required manufacturing tolerances vs. LFW capability. 6. Initial manufacturing costing based on material, lead time and manufacturing cost. 7. Joint lifing 8. Lead time to first blisk manufacture 9. Replacement blade requirements 10. Qualilty and strength of weld	Tooling impact Empirical, all knowledge types Quantified, structured and semi-structured Tooling impact, empirical, all knowledge types Tooling impact, empirical, all knowledge types Other (business strategy) Tooling impact, quantified, structured Other (costing) Other (physical properties) Other (business strategy) Other (in service) Other. (physical properties)

*Note: although specific examples of dimensions were featured in the data collection, these have not been included due to company confidentiality.

Table 5.2: Manufacturing knowledge requirements for preliminary design captured through informal discussion (continued)

Domain	Requirements	Coding
MFS manufacturing assessment	1. Manufacturing strategy (overall high-level process plan) 2.Is existing machine tool selection a constraint? Dimensions (determines geometry for process and is also base for cost model): Number of blades Chord length Blade height Stock remaining on annulus after roughing op Total accessible height during roughing ops Number of blocks Block distance Block depth Leading edge radius Trailing edge radius Fillet radius Annulus width Blade separation distance 3. For each operation: Tool info Assessment of cuts to be made Estimates of tool changes Tool manufacturer Tool type (description) Cutter material Coating Tool diameter Number of flutes L or RH flute Total cutting length per flat Number of cuts to achieve three flats Number of cuts (for other cuts) Total cutting length Number of blades per blisk (with one tool) Number of blades per tool Total cut depth Cut length for each tool Feed per tooth Feed rate M/C rpm Cutter speed Coolant Cutting time for each blade Total cutting time for all blades (i.e. total cutting time per blisk) Operating time for each blisk with safety margin.	Configuration impact, empirical, all knowledge types. Tooling impact All dimensions are empirical and structured unless otherwise stated. Manufacturing Geometry Impact, empirical and structured Other (costing)

*Note: although specific examples of dimensions were featured in the data collection, these have not been included due to company confidentiality.

- Their concerns at that particular stage of the design process.
- The main question which guides that stage of the design process.

Table 5.3 shows the concerns and guiding questions for each domain. These were deduced from the interview transcripts.

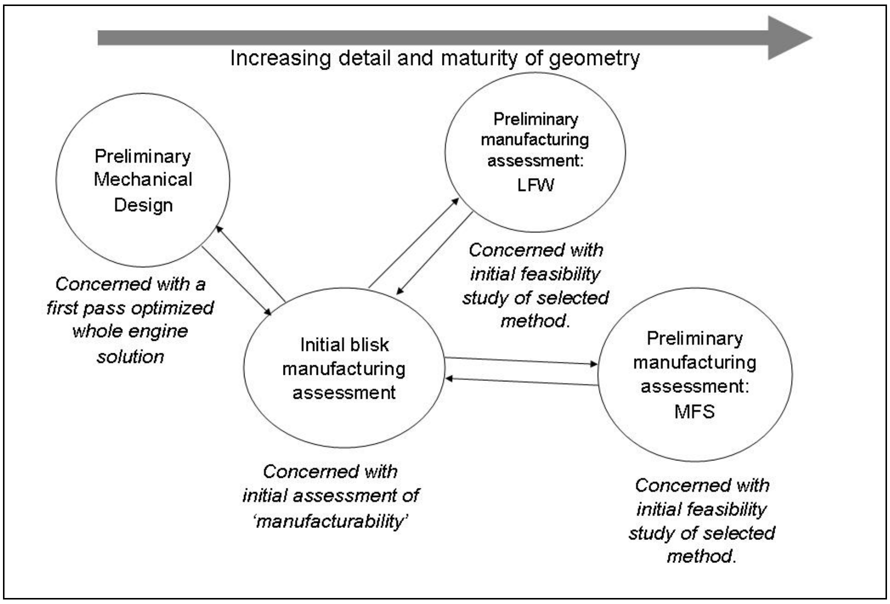


Figure 5.2: Acquisition and sharing of knowledge: domain concerns and interaction during preliminary design process

Table 5.3: Initial analysis of concerns, guiding questions and criteria for each Specialist Domain

Specialist domain	Concept Design (from preliminary design interview)	Preliminary Mechanical Design	Preliminary manufacturing decision	Preliminary manufacturing assessment: LFW	Preliminary manufacturing assessment: MFS
Concern		Concerned with a first pass optimized whole engine solution	Concerned with initial assessment of 'manufacturability'	Concerned with initial feasibility study of selected method.	Concerned with initial feasibility study of selected method.
Guiding question	What are the engine design trends?	Do you want a conventional blade / disc assembly or a blisk?	What method of manufacture will be used?	What machine is this going on?	What machine is this going on?
Criteria required to answer question.	Core size is reducing (geometric constraint) Core speed is increasing (higher hoop stress at rim)	*Well defined* Available geometry (from core size) Rim hoop stress (from core speed) Weight *Not so well defined* Repairability 'Manufacturability' (Method of manufacture, capability and maturity) Manufacturing cost.	What's the configuration envelope? (available geometry) Current convention: Stage 1: LFW Stages 6-8: MFS Stages 2-5 depends on geometry. Decisions driven by relative cost of one method to another (as it's based on material removal) What materials? (MFS tends to be used if disc and blade have same material)	Forge load (requires specific dimensional knowledge to calculate*). Machine dimensional constraints. What materials are to be welded? What's the maturity of the process? Has this been done before? Ref. previous project and MCRL level.	Assessment of geometry of component is required, both in its raw ('condition of supply') and finished forms in order to assess best machining centre fit and tooling access. Material is also important to assess the most suitable tooling inserts for cutting.

*Note: although specific examples of dimensions were featured in the data collection, these have not been included due to company confidentiality.

The different requirements for each domain have been interpreted as examples of different 'thought worlds' (Dougherty, 1992). To determine the reasons for these thought worlds would require additional investigation, however from the requirements capture results, the following potential reasons are suggested: the design process itself; the various tasks within the design process which are required to assess manufacturability; the knowledge and experience of individuals within each domain; the resulting incompatibility of maturity of geometry at each stage and the limitations in dealing with changing design requirements. Each 'thought world' is illustrated by the concerns and rationale of each domain in table 5.3. The interactions of the domains are clearly of prime importance in knowledge sharing, as illustrated by the existence of the process gap (see section 5.4.3) and the actions that were taken to resolve it.

5.4.2 Categorisation of knowledge according to the developed code

The increasing detail and analysis as the design progresses (see table 5.2) can be illustrated by categorising the manufacturing knowledge requirements according to manufacturing impacts and impacts of expression, in line with the developed code.

During preliminary design, the designers are primarily interested in knowing the definition of the configuration envelope (configuration impact) for the available methods of manufacture (LFW and machining in this case). The definition of the configuration envelope takes place in further domains and is primarily illustrated in all further cases by a tooling impact. Hence, the main driver for the configuration envelope for the blisk is the ability of the component to fit into a specific machine tool. However, a complete assessment of this requires far more assessment of the geometry than is available during the preliminary design. In table 5.2, the majority of these dimensional assessments are termed as 'empirical' to reflect the iterative and ongoing assessment of the component at this stage. However, the required knowledge is termed as 'structured' because ultimately the knowledge (dimension) is required in a numerical form.

In some cases the tooling impact has been quantified. An example of this (reference table 5.2) is with the assessment for LFW as outlined in the tool design report. In this case, some dimensional limitations on the available machines were quantified and shown in the tool design report as structured and semi-structured knowledge (numeric with supporting text).

As the manufacturing assessment became more detailed it appeared that more of these manufacturing impacts needed to be expressed in a quantitative way. When considering a process in development it may not be possible to quantify the impacts immediately. However, this could be a useful guide to the main knowledge attributes which need to be repeatedly assessed. By identifying these impacts it may be possible to increase awareness of the knowledge that needs to be known and quantified 'in the future', hence the design and manufacturing assessment teams could focus on identifying and obtaining that knowledge for more effective knowledge sharing.

A further observation is the existence of other impacts on the configuration envelope that are not strictly manufacturing-related but also need to be considered. These have been marked as ‘other’ in table 5.2, but mainly appear to address physical properties (such as stress and lifing requirements), cost implications and in service support requirements. Although out of scope of this particular study, they may be worth investigating at a later date.

5.4.3 Process Gap

The differences between the domain requirements indicate that a suitable manufacturing feasibility analysis appears to depend on a state of design maturity greater than that available as an output from the preliminary design stage. This was expressed by the need for quantified expressions of impact and structured knowledge. This can be illustrated by comparing the output at the end of stage 1 preliminary design (the 2D GA) with the inputs required at the beginning of stage 2 for linear friction welding. The GA did not provide all the level of detail necessary for the initial manufacturing assessment at the next stage. Consequently the additional detail required was initially assessed by scaling a previous design. This difference in requirements therefore appears to create a ‘gap’ in manufacturing knowledge in the product introduction process.

Historically, the project would have progressed as expected and these manufacturing knowledge gaps would be addressed in the later detail design stage (beyond stage 2) of the process. However, in line with market competitors, the lead time for new engine development has been reduced to 24 months. This has created a need for even greater concurrency between domain specialities. Therefore, in order to mitigate risk in the design solution, potential manufacturability problems need to be addressed earlier in the design process. It is suggested that this does not appear to be addressed by the current product introduction process, hence the process gap. Consequently the organisation has created an additional new process step to bridge this gap through the initial manufacturability assessment carried out by the sub-system team. This is a new informal process step created specifically for a new engine project. The need for such activities is greatest for risk mitigation for components in the engine architecture with new configurations, new materials and / or new manufacturing processes. Perhaps knowledge sharing could be improved by considering the manufacturing knowledge requirements necessary to address this process gap.

5.5 Study of Domain Interaction

The requirements capture activity for the blisk component revealed a gap in the design process during the preliminary design stage. It has been suggested that the reason for this was the reduction in the lead time for new engine projects driving the need for the design process to evolve. Consequently the knowledge sharing requirement had evolved but had not been formally reflected in the design process. The presence of the process gap had highlighted the different ‘thought worlds’ quite significantly. By examining the rationale for each specialist domain, the requirements activity was able to provide some explanation for the different ‘thought worlds’. However, for an engineer working within a specific domain, the rationale for other domains which interacted with theirs was not evident.

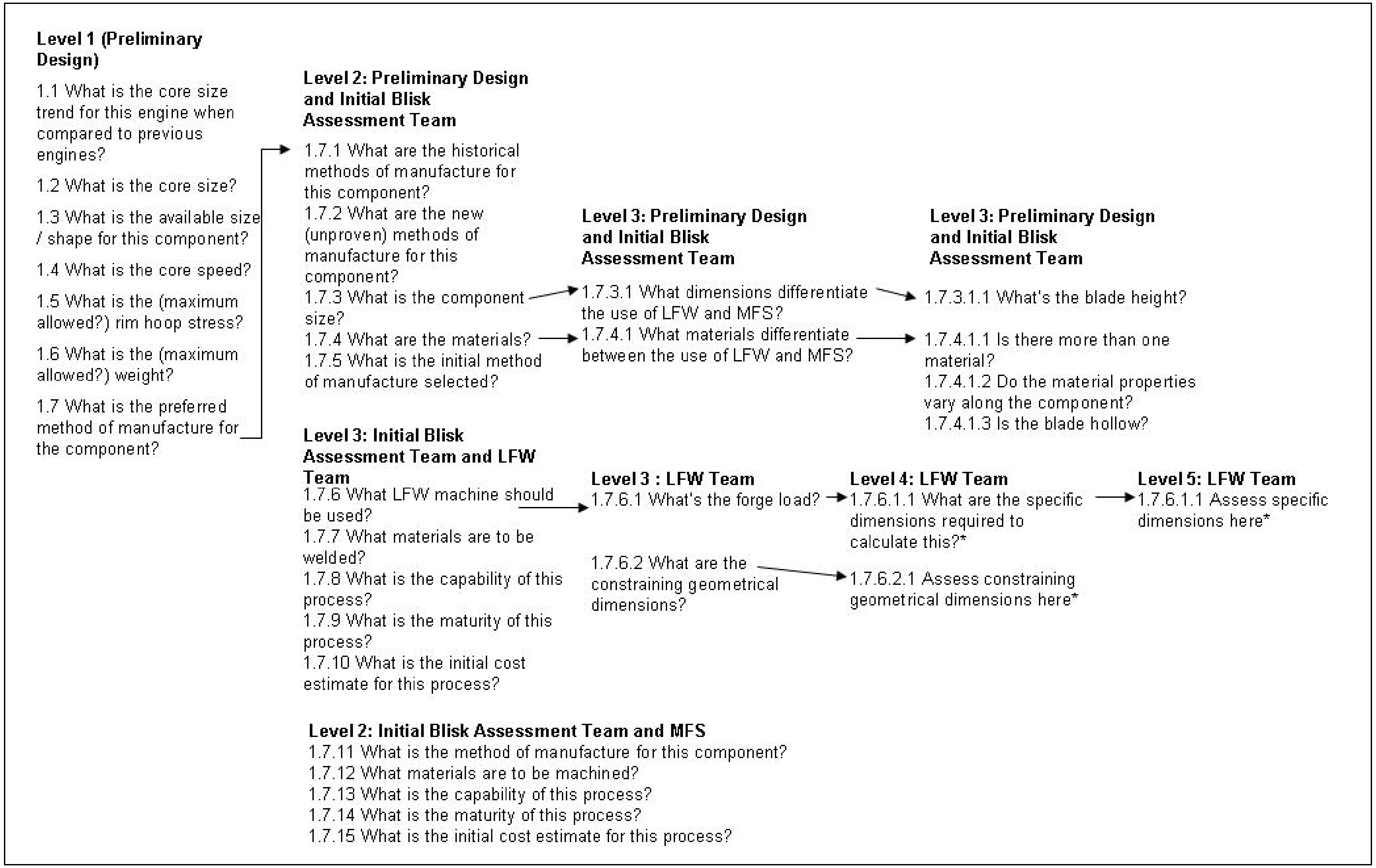
The study therefore needed to consider a method of identifying and acquiring manufacturing knowledge for assessment during preliminary design in order that it could be shared between the specialist domains effectively. The difference in specialist domain knowledge requirements due to differing rationale would always exist and would be required to compile and manage the manufacturing knowledge to assess a process for a component. Conversely, defining the manufacturing knowledge according to a specific stage of the design process may not be effective because this would not allow for any changes if the design process needed to evolve.

The approach therefore adopted by this study is to utilise the different perspectives ('thought worlds') of the domain specialists to build the required knowledge. Rather than define knowledge prescriptively for different stages of the project, a more flexible method would be to consider the interactions between the different domains to specify the knowledge according to each specialist's rationale. A way to knowledge acquisition would be to map out a schematic diagram to show the knowledge requirements for each domain and how they interact. Consequently the knowledge would be better organised and have the following advantages:

1. It would provide a view of the overall knowledge requirements for initial manufacturing assessment and its variations between specialist domains. This would be available to all involved in the assessment and give an appreciation of how each domain – specific assessment influenced the final outcome of the assessment.
2. As the knowledge flow would be shown between specialist domains rather than specific design process stages, the resulting knowledge schematic would not be tied to specific stages of the process. This means that it would be independent of the design process and therefore more flexible and adaptable to any future process changes.
3. By categorising the knowledge requirements as 'configuration impacts' and 'tooling impacts' an assessment of the necessary detail to define the knowledge could be included.

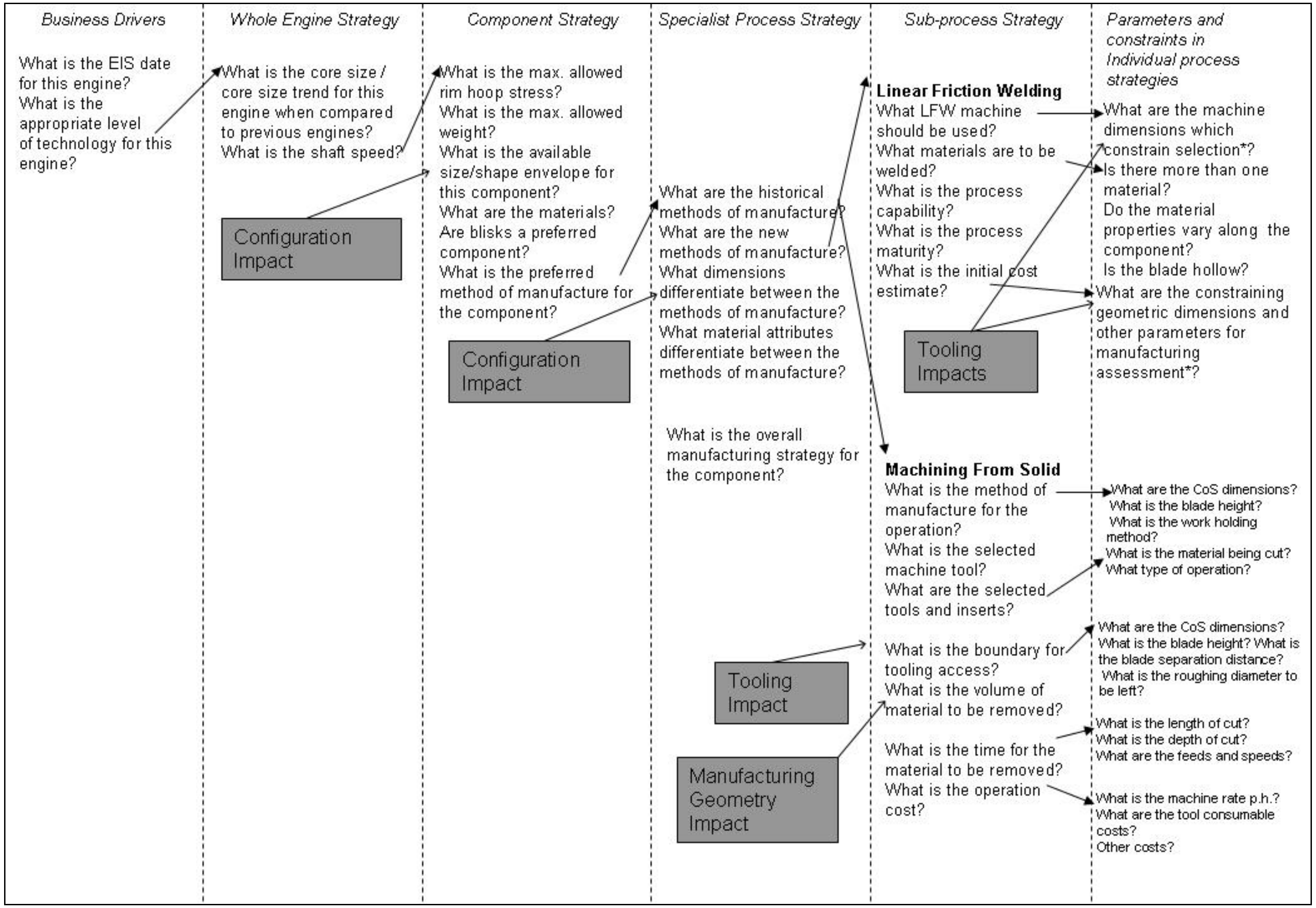
The data collected for the requirements capture was therefore analysed as a study of domain interaction as a first step to investigating more effective methods of sharing knowledge.

The starting point was the guiding questions as shown in table 5.3. However, it was clear that a number of questions (sub-questions) were required in order to obtain the answers to the overall guiding question for each domain. By doing this, the list of knowledge obtained from the study of the blisks was formatted into a list of questions which could be specifically asked for the component and process. For each question, a number of sub-questions were deduced, the answers to which would provide the answer to the overall question. Each sub-question was then sub-divided further into more levels of detail to provide the answers where necessary. In doing this, the purpose of the framework of questions was to create a set of repeatable questions which could be used for the blisk component to provide an initial manufacturing assessment in preliminary design. This would create a repeatable method of compiling



*Note: although specific examples of dimensions were featured in the data collection, these have not been included due to company confidentiality.

Figure 5.3: Initial diagram of domain interaction for manufacturing assessment (expanding LFW as an example)



*Note: although specific examples of dimensions were featured in the data collection, these have not been included due to company confidentiality.

Figure 5.4: Diagram of domain interaction following feedback

the knowledge and a method to solve the difference in requirements and knowledge maturity at preliminary and detail design. These questions were then represented as a diagram flowing from left to right. The initial findings are shown in figure 5.3.

This initial version was then fed back to and iteratively discussed with each of the domain specialists to verify that the knowledge recorded was complete and correct and to make changes where necessary. A main finding was that the 'levels' at could be applied to particular strategy levels: business drivers, whole engine strategy, component strategy, manufacturing process (decision) strategy and sub-process strategy. A further level of parameters and constraints was introduced where numerical answers to the questions could be specified. The final version of domain interaction after iterative feedback is shown in figure 5.3. Here, the manufacturing impact categories have been superimposed on top of the diagram by the author for the benefit of assessing the knowledge requirements.

For the specific component and manufacturing processes investigated, the diagram is a useful method of illustrating the level of detail required to answer what may be initially perceived as a simple question. For sub-questions where the answers can be derived as numerical constraints (such as machine tool selection for linear friction welding) there can be up to five sub-levels of questions. For answers where the criteria is more qualitative and perhaps more uncertain, there are fewer levels of sub-questions.

5.6 Summary

The starting point for the work in this chapter was the results of the first data collection. As the conceptual framework developed was abstract, further investigation was carried out into the blisk, a component specifically selected as a component of particular importance during preliminary design because it affected the sizing and performance of the engine. The manufacturing processes for the blisk also affected the component configuration envelope, especially as one of the processes, linear friction welding, was in development. Consequently the case exhibited criteria which had been highlighted as of interest in chapter 4. The activity also presented the opportunity to carry out an initial validation on the hypothesis of knowledge requirements which had resulted from the first data collection activity.

The analysis of the second data collection demonstrated that far from being a straightforward activity, the acquisition of manufacturing knowledge requirements can vary due to differences in specialist domains and the knowledge required therein, identified as different 'thought worlds'. For the particular case explored in this thesis, i.e. innovative manufacturing knowledge, this creates an element of risk in assessing manufacturing feasibility during preliminary design. A further contributing factor to this risk is the difference in the maturity of the design geometry between the preliminary and detail stages of the processes. The external influence of the reduction of the time to market had led to a 'gap' in the existing design process where more manufacturing assessment was required earlier in the process in order to address the risk of introducing new methods of manufacturing. This gap had been informally addressed by the introduction of a new manufacturing feasibility assessment team, however it was concluded that the design process had not sufficiently evolved to cater for this change in the time to market.

The knowledge identified could be expressed using the coding developed in the first data collection activity. It was expressed as a configuration impact at the more strategic levels of the process, yet required additional quantified and therefore more detailed knowledge (tooling impacts) as the design activity progressed. This was a demonstration of the hypothesis of knowledge requirements developed from the first data collection activity, showing that knowledge is expressed differently as it matures and that different knowledge types were required to show this.

It became clear that manufacturing knowledge acquisition depended on interaction between different domain specialists to bridge any gaps in the design process which may evolve. A method to acquire knowledge for the particular component and methods of manufacturing investigated was therefore considered. A study into interactions between the different specialist domains gave an overall picture of the questions which needed to be answered in order to supply the knowledge for each domain. This could be used flexibly rather than tying the identification of knowledge to specific stages of the design process.

This activity demonstrated that a collation activity of technical knowledge is insufficient for successful knowledge management. Successful knowledge management instead depends on being able to identify and acquire the content and level of knowledge which can be commonly shared between specialist domains in order to carry out an initial manufacturing assessment during preliminary design and hence mitigate the risk during this stage. Having explored this for a specific component and manufacturing processes, the next stage of the study will be to develop this work into a practical methodology to be used for effective knowledge sharing. This will be developed primarily for components of particular importance to preliminary design which use manufacturing processes in development and will be explored in chapter 6.

Chapter 6

Development of a Methodology for Effective Knowledge Sharing

6.1 Introduction

The two data collection activities outlined in chapters 4 and 5 provided a detailed investigation of the nature of manufacturing knowledge required during the preliminary design process. The first data collection produced an abstract conceptual framework identifying the manufacturing knowledge required, highlighting the importance of considering the maturity of the manufacturing process and the need to use both explicit and tacit components of knowledge for innovative manufacturing processes under development. The second data collection explored these findings further, considering the acquisition of manufacturing knowledge for a specific component with an innovative manufacturing process. These findings highlighted the need to combine the views of a number of specialist domains to effectively identify and share the knowledge content requirements. As an output of the analysis, a diagram of domain interactions was created to provide a means of sharing the knowledge more effectively between these different domains.

This chapter consolidates the findings of the two data collection activities and investigates how they can be used for effective knowledge sharing, thus addressing research objective 3. A systematic methodology is created for use at an operational level by designers and manufacturing engineers to identify, acquire and share manufacturing knowledge requirements during the preliminary stage of the design process. The rationale for the methodology is discussed, followed by an assessment of the methodology requirements and a discussion of its components. This is then followed by a description and example screenshots of the pilot methodology to be used in a validation study.

6.2 Rationale for a Methodology

The first step for this part of the study was to consider the findings from the two data collection activities. For the first data collection activity, the manufacturing knowledge requirements were analysed and categorised as manufacturing impacts (the effect on the configuration of a component) at varying levels of detail depending on whether they were being assessed during preliminary design (size and shape only) or at more detailed levels (in terms of tooling and manufacturing geometry impacts). These impacts were expressed in terms of how the knowledge was derived, from empirical (new process development) to standardised (repeatable process capability). These expressions were on a scale depending on the maturity of the process and a range of knowledge types on the explicit-taciet scale were needed to support them. Manufacturing processes in development also emerged as a key finding because they opened up new opportunities in terms of design capability, yet they were also risky because, being in development, the knowledge was less ‘known’.

Consequently the manufacturing knowledge of such a component was explored in detail for the second data collection activity. In this case, it was found that the knowledge requirements were a compilation of requirements from several specialist domains. Each domain had its own concerns and knowledge perspectives which guided its knowledge requirements. The knowledge requirements become more detailed (with an increasing need for more quantifiable knowledge) through interactions with domains from the later stages of the design process, however the results of these assessments need to be presented back at a more abstract level within the manufacturing assessment activity during preliminary design. This domain interaction was especially important in the specific case investigated (the blisk) in order to adapt to the demands of a reduced project lead time. This showed that more detailed analysis was initially needed during preliminary design in order to reduce the risk (i.e. make the knowledge more mature and ‘known’). A pragmatic approach was adopted for more effective domain interaction. Following from the example of the work by Hall and Andriani, and the research gap identified in chapter 2, some method of operationalising the conceptual framework was considered to be a suitable way forward (Hall and Andriani, 1998). Hence an operational methodology was developed.

6.3 The Methodology Requirements

The aim of the methodology is to enable the effective sharing of manufacturing knowledge during preliminary design by facilitating the interactions between the specialist domains which are necessary for identifying and acquiring the knowledge requirements and subsequent content. The methodology is aimed primarily at components that have undergone some degree of configuration change between subsequent design projects and therefore carry an element of risk. It is designed to give an initial feasibility assessment during the preliminary design stage.

There are two intended outcomes to this work. The first is that such a methodology will embody the findings identified during the data collection and analysis activities and consequently act as a means of testing the developed hypothesis. The second is that the work results in a systematic operational methodology to be tested on a range of components and processes within the organisation studied.

The requirements of the methodology are as follows:-

1. The level of knowledge required is that which indicates how the process impacts on the configuration envelope of the component. Each specialist domain has their own preferred level for discussing the manufacturing

requirements. However, the methodology should collate these to reach a desired level of common understanding and usage.

2. The content of the knowledge (for the purpose of sharing) must include some assessment of process maturity in addition to process feasibility, capability and estimated cost.
3. Knowledge must be conveyed using a mix of explicit and tacit knowledge methods.

Three components of the methodology were developed to fulfil these requirements:-

1. A generic domain interaction diagram to identify the relevant knowledge requirements.
2. A process maturity audit to assess the manufacturing processes.
3. A workshop-based pilot process to be used for tacit and explicit knowledge sharing.

These components originated from the findings of the data collections. They, and the methods used to develop them will be discussed in the next section.

6.4 Methodology Components

6.4.1 Generic diagram of domain interactions

The generic diagram of domain interactions was designed to fulfil requirement 1. Its purpose was to identify the knowledge content requirements required at the appropriate level for an initial manufacturing assessment, while accounting for the variation in the content and level of knowledge according to each domain.

The foundation for the generic diagram was the diagram of domain interactions created from the blisk case study. However, being specific to that component and process, it required further development. The process for creating a generic diagram of domain interactions was similar to that used for the creation of the blisk-specific diagram of domain interactions. Iterative modifications were made to the blisk-specific diagram which were then fed back to stakeholders for their review and comments. These stakeholders were the same as for the second data collection, with two additional contacts. These contacts were consulted due to their business process knowledge and are summarised in table 6.1.

The first step was to modify the blisk domain interaction diagram into a list of generic questions, which is shown in figure 6.1. This was used as an initial template of questions used in the pilot evaluation of the methodology and evaluation session 1 (see sections 7.5 and 7.6). The subsequent feedback received suggested that these questions were still too tied to the linear friction welding and/or machining processes. A preceding step was required. The questions for identifying the knowledge varied according to the manufacturing process and would first need to be defined themselves. On closer examination of the generic questions, it appeared that all potential manufacturability issues fell into one of three categories – material properties, process or geometry. These issues were common to all processes and the feasibility of the process. These categories would be a better generic representation for the questions. Therefore the original diagram of domain interactions was replaced by a list of questions (see table 6.2) to identify the following set of *characteristics* specific to the component and process:-

Table 6.1: Additional contacts for the development of methodology

Specialist domain	Department	Range of knowledge
Specialist in development of design process (particularly inclusion of manufacturing knowledge)	Manufacturing directorate	Knowledge of design process requirements and deliverables across whole engine projects from manufacturing perspective.
Knowledge Management	Central Knowledge Management Department	Knowledge management best practice and initiatives across the organisation.

Material characteristics

These are aspects of the material properties of the component which constrain the method of manufacture available for selection (i.e the material properties of wood enable it to be successfully turned on a lathe but not vacuum formed).

Process characteristics

These are aspects of the manufacturing process which constrain its ability to manufacture the component. These can be categorised by the tooling or manufacturing geometry impacts, but also other aspects of production, such as capability and capacity.

Geometric characteristics

These are aspects of the component geometry which are constrained by the selected method of manufacture. These can be dimensions, overall shape and size or surface finish requirements. These can be categorised by the configuration impact.

Other characteristics

There may be other miscellaneous constraints on the manufacturing process selection which do not fall into the above three categories but still need to be considered, such as those found during the second data collection (i.e. cost, service requirements).

These characteristics can be represented as elements of the manufacturing impact, as shown in figure 6.2.

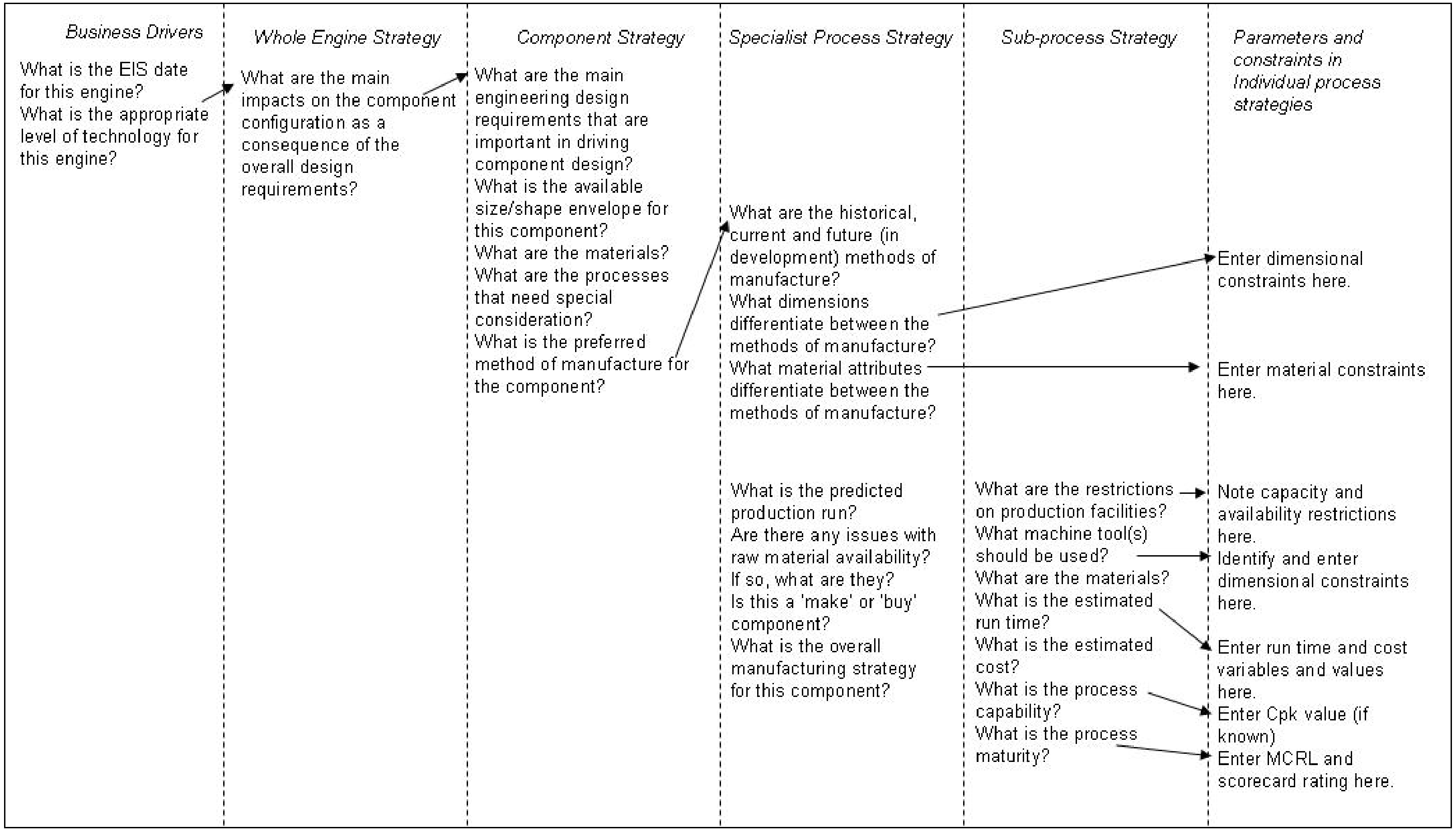


Figure 6.1: Generalisation of blisk diagram of interactions

Table 6.2: Generic questions for domain interaction

Comparing methods of manufacture / assembly:

What are the historical, current and future (in development) methods of manufacture / assembly to be considered and assessed in this workshop?
What are the characteristics of the component / assembly that differentiate between methods of manufacture / assembly?
What are the geometric characteristics?
What are the material characteristics?
Are there other characteristics? If so, record them at this point.
What are the characteristics of the process which influence the selection of the method of manufacture / assembly?
What is the predicted production run?
Are there any issues with raw material availability? If so, what are they?

Knowledge about specific methods of manufacture / assembly:

What are the characteristics of the component / assembly which determine the machine to be used?
What are the geometric characteristics?
What are the material characteristics?
Are there other characteristics? If so, record them at this point.
What are the influencing characteristics of process selection?
What are the restrictions on production facilities?
What are the capacity restrictions?
What are the availability restrictions?
Are there other restrictions? If so, record them at this point.
For run-time and cost estimation:
What is the estimated lead time? (Enter run time variables here).
What is the estimated cost? (Enter cost variables and values here).
What is the process capability? (Enter Cpk value if known here).
What is the process maturity? (refer to MCRL and process maturity audit here if known).

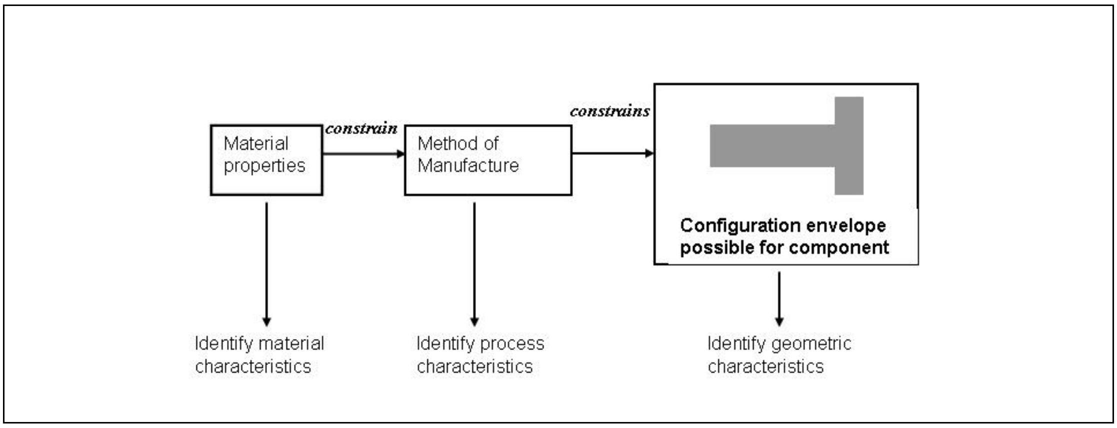


Figure 6.2: The manufacturing impact and material, process and geometric characteristics.

A further distinction between the characteristics was made in whether they were ‘differentiating’ or ‘influencing’. A differentiating characteristic is one which, if present, will determine that a particular manufacturing process must be used for manufacturing feasibility. For example, a blisk with hollow blades can only be produced by linear friction welding. Therefore, a hollow blade is a differentiating geometric characteristic because it drives the product introduction team to that selected method of manufacture. An influencing characteristic is one which will not determine a specific method of manufacture, but will provide supporting evidence, for example in a business case, for the selection of a particular method of manufacture. Cost is an example of an influencing characteristic.

6.4.2 Process Maturity Audit

The purpose of the Process Maturity Audit was to give a quick assessment of the maturity of the process to determine its applicability for a manufacturing feasibility assessment in early preliminary design. It was therefore designed to meet methodology requirement 2.

The foundation for the Process Maturity Audit came from the category ‘expression of impact’ developed in the coding of the interviews from the first data collection activity. Here, certain characteristics were used to determine ‘empirical’, ‘quantifiable’ or ‘standardised’ manufacturing knowledge. These expressions of impact related to the process maturity. An ‘empirical’ expression of impact denoted a process in development; if the knowledge was quantifiable then the process was mature and if the knowledge was standardised, so was the process.

With this in mind, a series of statements were created to describe a manufacturing process at each of the three states. Table 6.3 shows the original coding and the resulting indicators which may apply to a process in that state. These statements were initially used in the methodology during a pilot evaluation. However, due to some ambiguities in its interpretation it required further development (see section 7.5).

Table 6.3: Process maturity, definition and indicators

Process maturity (and definition)	Original coding definition	Process indicators
In development *(occurs when there is evidence of experimentation in determining the process limits and capability).*	*(Empirical expression of impact)* The manufacturing process will require some development work in order to meet the design requirements. Assessment of the process constraints on the product geometry will be from the results of experimental work or investigations.	- The process requires development. - The process capability is assessed via results of experimentation work. - Process is a development of existing manufacturing technology and is ready for productionisation. - This process is being applied to a new situation.
Mature *(Occurs when the component size can be restricted to pre-determined numerical limits which can be measured for process capability).*	*(Quantifiable expression of impact)* Reference to maximum or minimum allowed dimensions (or other limits) due to manufacturing. These dimensions are applicable to current manufacturing processes. These dimensional constraints can be seen across most components in the general arrangement. They will be considered routinely as part of the design process.	- Manufacturing minimums and maximums. - Limitations expressed as formulae, tooling size restrictions, algorithms, constrained dimensions.
Standardised *(Occurs when the component or feature configuration is restricted to a set of discrete values which have been pre-determined by the manufacturing process and may be linked to a prescribed process capability).*	*(Standardised impact of expression)* There will be an indication of a standardised component or feature. The reasons for standardisation may not be fully known.	- Problems associated with the manufacturing problem may be significantly reduced. - No customization is permitted. - The component / feature may have been manufactured for a number of years and a standard process / tooling may apply for all examples. - No further development of the manufacturing process is required.

The process indicators were therefore expanded into a series of statements which could be used to gauge the process maturity for a process under examination. These statements can be shown in table 6.4. The MCRL (Manufacturing Capability Readiness Level) is an in-house company process which uses detailed collated information to describe the maturity of a manufacturing process on a scale of 1-9. The MCRL process is described in appendix C.

Table 6.4: Process maturity audit

If the process is…	…*Then the following applies:*
In development	1. Process parameters (such as processing times, temperatures, forces, achievable component thicknesses or other dimensions) are derived from previous research or experience on related components and materials. Development work is required to specify these parameters for this particular case. 2. New machine tooling or new work holding methods are required for the component. 3. The process capability is not known and will improve with development work on the process. 4. The current MCRL level (if known) is 5-6.
Mature	1. Process parameters fall with a range, the limits of which have been specified from previous experience. Some adaptations may be required but the parameters will remain within this range. 2. Existing work holding methods may need to be adapted to accommodate the component. 3. The process capability can be measured and falls within a known range. 4. The current MCRL level (if known) is 7-9.
Standardised	1. Process parameters are restricted to a specified range. 2. Machine tooling, work holding methods and tooling may be standardised for component families. 3. The process capability is known and determines the limits permitted. 4. The current MCRL level (if known) is 9+.

The process maturity audit is useful in two ways. Firstly, the rating determines whether the component and its process have an element of risk which requires an initial feasibility assessment. This applies to 'in development' processes. 'Mature' processes may also be considered if they are to be compared to the process in development.

Secondly, the rating indicates how the manufacturing knowledge is likely to be expressed and the knowledge types which will be required to record and share this knowledge. A process 'in development' correlates to an empirical expression of knowledge. Therefore all types of knowledge will be required, with the emphasis on semi-structured and unstructured. A mature process will be quantifiable, so can therefore be expressed using more structured knowledge, but also semi-structured to provide context. Finally, a standardised process will have standardised expressions of impact and can rely primarily on structured knowledge (although it would also be prudent to have some degree of semi-structured knowledge present).

6.4.3 Knowledge must be conveyed using both explicit and tacit knowledge methods

The purpose of this component (which fulfils the third requirement) was to determine the necessary formats for the methodology. Suitable media were required for the effective transfer of structured, semi-structured and unstructured knowledge. As seen in both the literature review and the data collections, the ability to express knowledge across the full explicit – tacit range was an important requirement. This was to enable the full range of manufacturing knowledge to be expressed depending on its maturity.

As has been discussed in chapter 2, this thesis takes the view that it is not possible to transfer unstructured (tacit) knowledge through an information system and the only possible method of transfer is person to person contact. Unstructured knowledge transfer requires face-to-face contact by domain experts. Therefore the method proposed for running the methodology was a series of workshops with guided discussion for effective knowledge requirement identification.

In addition to the tacit sharing environment during the workshops, knowledge relevant for sharing also would need to be recorded in both structured and semi-structured forms as follows:-
Structured: some knowledge may need to be expressed numerically (i.e. in a structured way).
Semi-structured: additional explanatory notes may also be required, both as supporting notes to the structured knowledge or in cases where knowledge cannot be quantified.

A series of pilot processes were therefore designed to be run in a series of workshop situations to guide them towards the desired outcome (see section 6.5). The final format of the methodology was therefore suited to a mix of guidance notes through the workshops and forms for recording and displaying the required manufacturing knowledge for feasibility assessments.

6.5 Methodology

This section introduces the main methodology and demonstrates how the three components (as discussed in section 6.4) were put together with a systematic process.

6.5.1 Methodology Format

The eventual ideal format for a practical methodology in use would be a combination of a database in which relevant knowledge may be recorded and a web-based front-end. This would consist of a series of database forms to capture and present the recorded knowledge mixed in with a series of web pages to guide users through the methodology workshops. The front-end would sit within the organisation's intranet.

For the purpose of evaluating the methodology, a 'pilot' version was created using MS PowerPoint and Excel. It consisted of a series of slides run as a slide show with hyperlinks and action buttons. The aim was to mimic an intranet web site. In lieu of a database, links were created to an Excel spreadsheet. A further PowerPoint presentation was created to show the output of the methodology in a form to be used by the preliminary designers in making a feasibility assessment.

The reason for having the methodology in this format was to ensure a method of displaying each knowledge type. Structured knowledge would be recorded as values in the Excel spreadsheet and displayed as such in a suitable output form. Semi-structured knowledge would be displayed as text notes recorded directly in the Excel spreadsheet and output directly onto the output form.

6.5.2 Pilot Workshop Processes

The methodology is designed to be used at the beginning of the preliminary design stage of a complex mechanical product. Although the geometric model of the product will be incomplete at this stage, the design team will have a good indication of the components that will be featured (the design Bill of Materials) based on previous similar project concepts.

The design of the pilot workshop processes were based around finding the answers to the following three questions:-

1. What components (and their processes) require an initial feasibility assessment?
2. What is the manufacturing knowledge required for the feasibility assessment?
3. What is the best course of action, given the knowledge of the process feasibility?

Each question defines a pilot process created for the methodology to generate the answers. These pilot processes are named Select, Create and Use. Each pilot process – and its related question – is shown in figure 6.3.

The focus of this study is on identifying the appropriate manufacturing knowledge requirements which need to be shared and then defining this content. Therefore the main focus of the methodology development has been the two pilot processes which are used for this - Select and Create. For the Use process, the preliminary designers are presented with the knowledge which has been created in a template which can be used for future reference, however a complete Use process would then incorporate this knowledge into the preliminary design process. Some ideas on how this could be achieved are discussed in this section in due course. In order to complete a knowledge sharing cycle it would be prudent to include a Review process to ensure that knowledge is kept up to date, although the definition of this part of the process again would require further work – some ideas on how this could be achieved follow. The links between the 'use' and 'review' processes are shown as dotted in figure 6.3 to indicate the further development that would be required, however they are included for completeness.

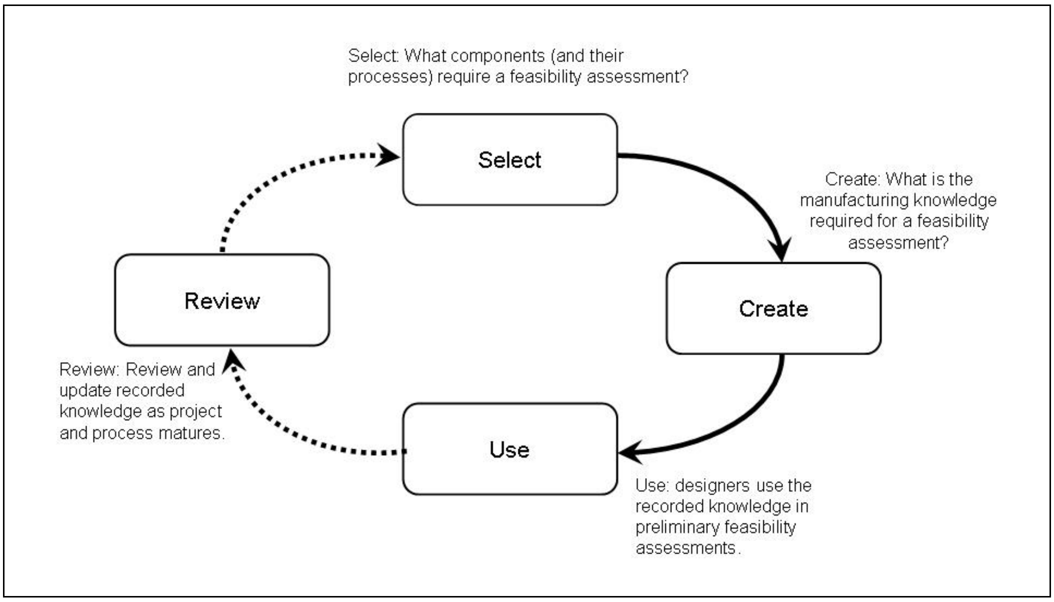


Figure 6.3: Pilot Workshop Processes for the Methodology

The Select Process

As the methodology is designed to be used on components with manufacturing process risks, it follows that it will not be relevant for every component. This first process is therefore an audit to determine which components (and their processes) should be considered. This process takes place in a workshop which involves experienced representatives of design and manufacturing. It is designed to be run quickly and intuitively, relying on representatives' experience and judgement.

The steps in the workshop are as follows:-
1. A list of components is compiled from the Bill of Materials.
2. The relevant processes are listed.
3. Each is quickly scored using the Process maturity audit.
4. The results are filtered. Component / process combinations deemed to have some element of risk are then listed for subsequent processes. An element of risk applies where at least one of the following applies: there is a new component configuration, a new material is being used or a manufacturing process has been scored as 'in development'. Figure 6.4 shows the Select process steps. Screenshots of each step of the PowerPoint presentation are shown in appendix D.

The Create Process

As with the Select process, this process is workshop-based to draw together manufacturing experts and solicit knowledge from them in a systematic fashion. There are two stages to the Create process. Because the methodology is generic, the knowledge which is required for the selected component / process combination must first be defined. This is the first stage, called the ‘Decide Knowledge’ workshop. Once this has been completed, the second ‘Record Knowledge’ workshop is used to record the specific manufacturing knowledge.

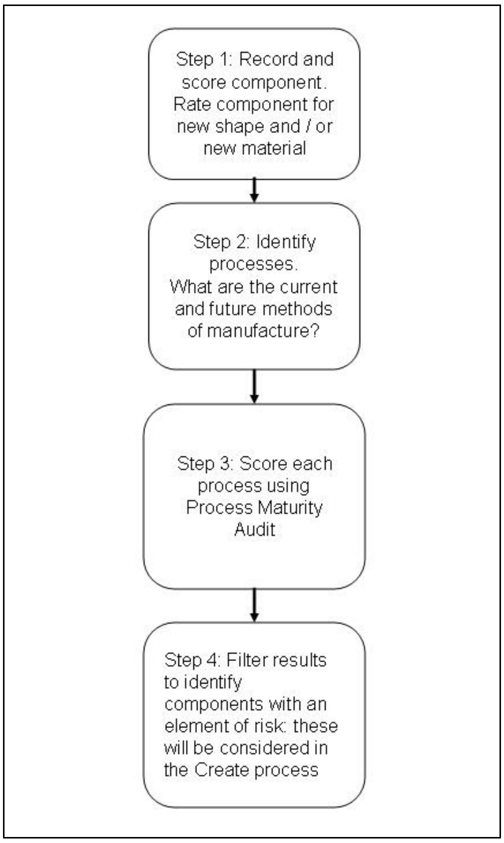


Figure 6.4: Select Process Steps

For the ‘Define Knowledge’ workshop, the participants define the material, process and geometric (and other) characteristics relating to the component and methods of manufacture. There are two levels to this process. At level 1, the manufacturing knowledge to compare methods of manufacture is identified. At level 2, the knowledge required for an assessment of each specific method of manufacture is identified. The process for this stage is shown in figure 6.5. This information is recorded on a ‘Create’ form in Excel.

For the ‘Record Knowledge’ workshop, the knowledge relating to the characteristics are recorded. The characteristics are then categorised as differentiating or influencing. Differentiating characteristics differentiate between different methods of manufacture. Influencing characteristics provide supporting ‘evidence’ which could be used in a business case. Where the knowledge can be numerically defined, this is noted, together with any caveats which may apply. If the knowledge cannot be quantified a brief descriptive note is added to explain why this characteristic is important in determining manufacturing feasibility. The process for this is shown in figure 6.6. Screenshots of each step of the PowerPoint presentation are again shown in appendix D.

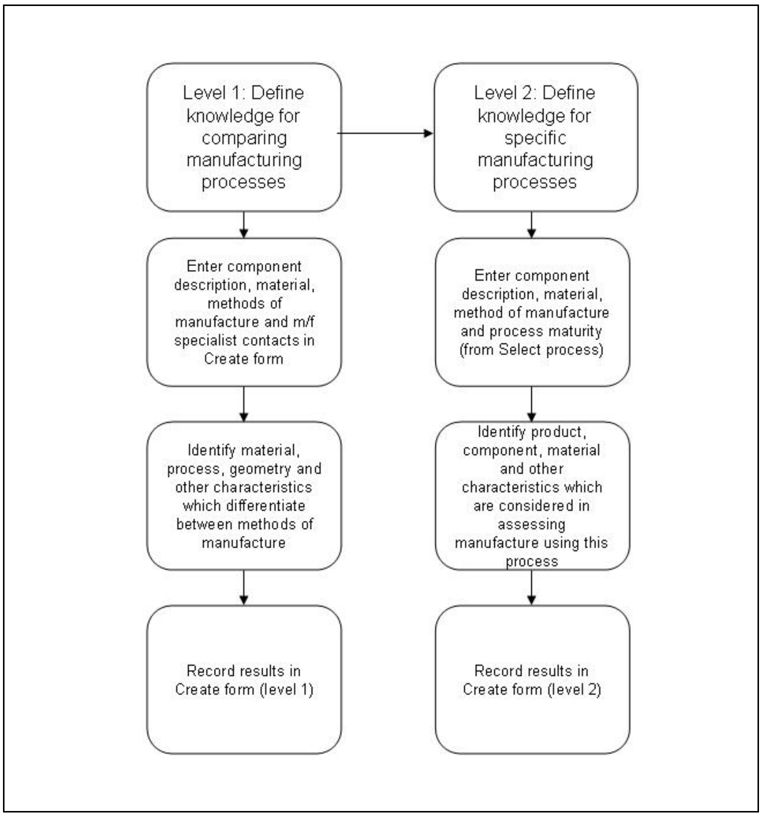


Figure 6.5: Create Process 'Decide Knowledge' process steps

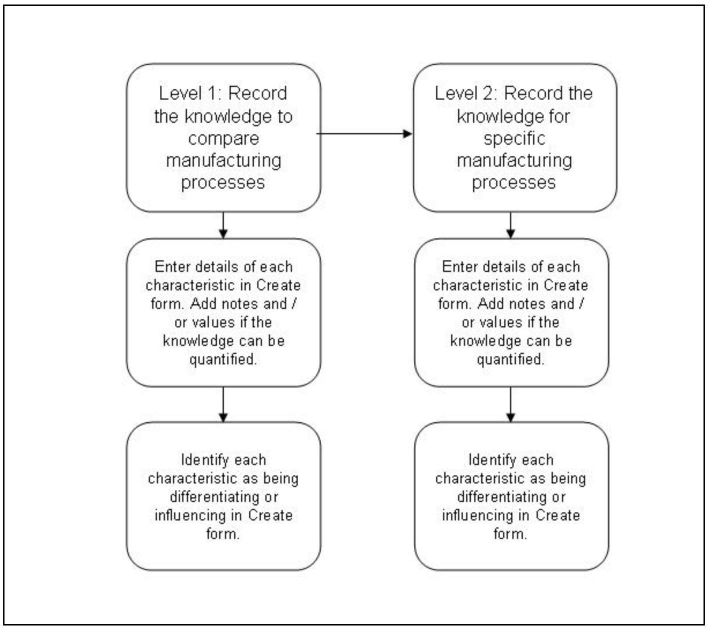


Figure 6.6: Create Process 'Record Knowledge' process steps

The Use Process

A form was designed to display the knowledge recorded during Create process to the preliminary designers. It was designed to acquire the knowledge from each of the specialist domains and present it collectively to give a comprehensive view of the manufacturing knowledge requirements for preliminary design. The form was designed to present the knowledge in a user-friendly way for future investigation and feasibility assessment work. Example screenshots of 'dummy' forms (used to demonstrate the methodology to the organisation) are shown in appendix D.

The intention behind the form is that it could be actively used for an initial manufacturing assessment. To fully integrate the knowledge identified and acquired into the design process, some ideas must be generated on the potential ways in which this knowledge could be used and the formats in which it could be used effectively. It would not be suitable, for example, to integrate this knowledge with a KBE system or similar as the knowledge is not yet suitably mature for such a system. Other more reference-type systems would be a better option. However, the risk is that the form itself would become out of date very quickly if it were to be used just as a reference tool and the credibility of the recorded knowledge would become undermined. Active use would therefore have to be combined with an ongoing Review process to maximise its value.

Review Process

The review process for this methodology would be concerned with the review and update of the knowledge recorded. The maturity of a manufacturing process is a time-based activity. As time and a project progress, processes originally recorded as being 'in development' will become 'mature'. Knowledge relating to the characteristics may go from being notes to quantified parameters. Knowledge which was originally quantified may have changed parameters due to the results of development work. A review activity, possibly again workshop based, would need to be developed in order to keep the knowledge updated. The main emphasis of this would be to keep the review sessions timely but ideally not too time-consuming, as again there may be a tendency for the activity to reduce and the methodology to fall out of use. Once the knowledge relating to a specific project had been defined during the 'decide knowledge' workshop, the initial identified characteristics could be reused for subsequent projects and comparisons made between previous projects. Over time, this may actually reduce the amount of time required for the methodology sessions.

6.6 Summary

The hypothesis of manufacturing knowledge requirements generated from the two data collections was integrated into an operational methodology to be used to identify, acquire and share the manufacturing knowledge requirements for an early assessment of manufacturing during preliminary design. This methodology draws on both the manufacturing impacts, assessment of process maturity and knowledge types from the first data collection and the interactions between the different specialised domains from the second data collection. A pilot version of the methodology was developed using a combination of MS PowerPoint slides which directed the users through a series of workshops and MS Excel spreadsheets to capture the knowledge requirements and contents. The methodology now requires evaluation for two reasons. The first is as a means of validating the hypothesis of manufacturing knowledge requirements generated. The second is to evaluate the methodology as an operational tool within an industrial setting. The evaluation will be discussed in chapter 7.

Chapter 7

Evaluation of the Methodology

7.1 Introduction

The previous chapter discussed the development of a methodology to identify, acquire and share innovative manufacturing knowledge between designers and manufacturing specialists during the preliminary design process. This work formed the first part of the hypothesis-testing phase of the study. The methodology had been created as the embodiment of a hypothesis of innovative manufacturing knowledge requirements. This hypothesis had been developed during inductive phase of the study from the analysis of two data collection activities - from exploratory interviews and an investigation into a component with an innovative manufacturing process.

To conclude the hypothesis-testing phase of the study, the methodology required evaluation for two reasons: firstly, to verify (or otherwise) the hypothesis developed and secondly to evaluate the effectiveness of the process, highlight its strengths and seek suggestions for future improvements. In doing this, the work addressed research objective four: To evaluate whether the method developed in objective 3 presents an effective way of identifying, acquiring and sharing the knowledge requirements between domain experts.

This chapter discusses the design considerations, execution and results of three evaluation sessions using different components and manufacturing technologies. It details the aim and scope of the evaluation, the considerations for the evaluation design, the design of a survey to elicit data for evaluation and the subsequent analysis and findings. The evaluation sessions took place over a four month period.

7.2 Evaluation Design

There were three factors which needed to be considered in designing a suitable method of evaluation for the methodology. These were:-

1. The aims and objectives to be achieved by evaluating the methodology;
2. Evaluation scope: the methodology processes to be included within the evaluation and the range of organisational activities to which they should be applied;
3. General evaluation design considerations.

Each factor is addressed in the next three sub-sections.

7.2.1 Aims and objectives

The evaluation aims originated from research objective four. The first was to verify the hypothesis developed. If the hypothesis was confirmed, then the following ideal outcomes would result from the evaluation:-

1. The manufacturing knowledge requirements identified (specified by the material, process and geometric characteristics) would be sufficient to enable an initial feasibility assessment of the manufacturing process to be completed during the preliminary design stage.
2. The manufacturing knowledge level would be appropriate for an initial feasibility assessment during the preliminary design stage
3. The manufacturing process could be expressed in different ways according to the process maturity.
4. Combinations of different knowledge types could be used to express this process maturity.
5. The above combinations would be an effective way of knowledge sharing between the specialist domains of design and manufacturing.
6. The use of the methodology would enable the effective compilation of the manufacturing knowledge.

A definition of ‘effective’ in this case meant that the methodology was user-friendly and that all the knowledge required across different domains was identified and collected quickly and efficiently.

The second aim was to examine the suitability of the methodology in effectively identifying, acquiring and sharing innovative manufacturing knowledge for a preliminary design assessment. This aim indicated that some application of a methodology would be required in a practical situation.

The objectives of the evaluation session were therefore:-

1. To design a suitable evaluation scenario which would enable the methodology to be applied to a suitable range and number of situations where appropriate manufacturing knowledge could be generated and shared. This would evaluate both the hypothesis and the general use of the methodology.
2. To design and implement a method of data collection during the evaluation session to confirm the success (or otherwise) of the six outcomes above.

These aims and objectives influenced both the scope of the evaluation and the evaluation design.

7.2.2 Scope of the evaluation

The scope of the evaluation encompassed two elements. The first was the methodology processes which would be relevant for the evaluation. The second was the application of the methodology in the wider, organisational context, in line with the aim to evaluate it in a practical situation.

To achieve the ideal outcomes in section 7.2.1, innovative manufacturing knowledge would need to be identified and acquired. Consequently the Select and Create processes required evaluation. The knowledge acquired would then need to be evaluated on its suitability for use in preliminary design. It would therefore need to be evaluated by preliminary designers on its suitability for use, although this would not involve the full Use process.

As the methodology was developed for the product introduction process of a specific company, it would be prudent for the evaluation to take place within the same context. The decision was taken to explore the use of the methodology for three different components, comparing two manufacturing processes for each. In doing this, the evaluation would take the form of a single embedded case study (Yin, 2003).

7.2.3 Evaluation design considerations

The evaluation activity was designed to examine the methodology with a view to further improvement and development. This fits the requirements of a formative evaluation as defined by Patton (Patton, 1987). Central to this was an evaluation of two of the methodology processes – Select and Create – in compiling the required knowledge, which entails a process evaluation strategy. Both strategies require the use of qualitative data in order to *'provide depth and detail about the program's strengths and weaknesses'* (Patton, 1987, p.29).

Patton lists three important considerations for evaluation design (Patton, 1987, p.166):

'What is worth knowing about the program? What data will be most useful? How can the design be appropriately matched to the evaluation situation, the stage of program development and the primary information needs of stakeholders?'

The evaluation aims considered the first question for the entire methodology. In addition to this the Select and Create processes needed consideration at a more detailed level. For the Select process, the concerns were:

- Is this a quick and effective way of highlighting components which will require further scrutiny?
- Is the process maturity useful knowledge?

For the Create process, the following questions were important:

- Do the characteristics capture the knowledge requirements for an initial feasibility assessment?
- Are they to the correct level of detail?
- How does the use of different knowledge types and 'expressions of impact' affect knowledge collection and recording?

- How well did the methodology process work?

In evaluating the knowledge acquired, these were the concerns:

- Does the knowledge recorded during the Create process provide manufacturing knowledge with the correct content and level of detail to enable an initial process feasibility assessment to take place?
- How does the use of different knowledge types and 'expressions of impact' affect knowledge use?

For Patton's final question ('how can the design be appropriately matched to the evaluation situation, the stage of program development and the primary information needs of stakeholders?'), the methodology had been developed to a stage where an evaluation of a pilot was required. It was neither necessary nor desirable to run the methodology as part of a new product introduction project as its use had not yet been fully investigated. However, it was sensible to evaluate the project using a series of workshops which would, as far as possible, mimic how the methodology would be run in practice. The selection of real components would enable the knowledge to be collated to the required level of detail with an awareness of the problems involved in selecting a manufacturing process at in a real-life situation.

Patton maintains that, in qualitative validation, *'the power of purposeful sampling is in selecting information-rich cases for study in depth'*(Patton, 1987, pp.51-52). Consequently a purposeful sampling approach was adopted. In the case of this particular evaluation, the richness of information was determined by the specific cases selected.

The cases were selected to conform to Patton's definition of deviant case sampling (Patton, 1987, p.52) in that they are *'rich in information because they are unusual or special in some way'*. They were relevant because they comply for the criteria for which the methodology was designed, however in the sponsoring company this design situation would be considered as being unusual. The selection of these types of cases therefore assisted in testing its suitability for practical use, even though this was not a prime purpose of the evaluation.

As the most useful data from the evaluation would provide answers to these detailed process questions, a means of questioning was needed to elicit such answers. The most useful answers would be exploratory, with additional insights into to the strengths and weaknesses of the methodology and the participants' own ideas for future improvements. A qualitative approach was therefore adopted.

Options considered for qualitative data collection were semi-structured interview, survey or workshop observation. Qualitative surveys were selected as a suitable research design method for this study because they are an effective way of examining participant's attitudes to a series of set criteria. The completion of a survey by each participant was included as an activity in each evaluation session.

7.3 Evaluation Session Design

As discussed in section 7.2.2, the evaluation was designed around the identification and sharing of manufacturing knowledge pertaining to three different cases, each a component with two methods of manufacture. The components for evaluation were:-

1. An assembly, investigating two different joining methods. One joining method was a mature process which had been successfully used, the second was a new process offering significant advantages which was still under development. The assembly is two joining stages of a compressor. The current joining process was electron beam welding (EBW); the process in development was inertia welding (IW).
2. A component, again investigating two different manufacturing processes, of which one was mature and the other a new process approaching productionisation. The component was the HP compressor case. The current method of producing the case was by forging and machining; the process in development for consideration was near net form (hot isostatic pressing, HIP).
3. A specific component feature, again investigating two different manufacturing processes, the first being mature and the second in development. This was the honeycomb feature of the HP Seal Segment, which creates an abradable seal. The current method of producing the honeycomb was with electro-discharge machining (EDM) and the process in development which could potentially be applied to the feature was direct laser deposition (DLD).

The components were deliberately selected to reflect the type of situations for which the methodology was designed. They were technologically intensive with at least one process deemed to be 'in development' according to the Process Maturity Audit and the other process considered 'mature'. There were three reasons for this. The first was to use the mature process as a basis for comparison for the new process in development. The second was to see if each process did indeed rate as 'mature' and 'in development' with the process maturity audit and the third was to compare the knowledge types required for each method of manufacture / joining. Selection of the above components and processes therefore met the criteria for deviant case sampling for which the methodology was designed.

For each of the three cases, two evaluation activities were required. The first was an evaluation of the knowledge identification and acquisition aspects of the methodology. This was named the Manufacturing Evaluation, referring to the manufacturing knowledge which would be collated. The second was the evaluation of the collated knowledge to ascertain its suitability for use in preliminary design. This was named the Designers' Evaluation. Sections 7.3.1 and 7.3.2 discuss these activities in detail.

7.3.1 Manufacturing Evaluation

The aim of this evaluation activity was to mimic a real-life scenario as far as was practical. Therefore the methodology was run as designed as far as possible using current components and processes. There were two concessions. The first was that a smaller number of people took part in the activity. The second was that two processes were considered for each session whereas in a real design project more may have required investigation. Otherwise, the data collected reflected the real situation (and all its ambiguities) as far as possible whilst allowing the methodology to be assessed for proof of concept.

The objective of the manufacturing evaluation was the identification and acquisition of manufacturing knowledge requirements deemed relevant for an initial feasibility assessment for two processes. The activity was run as a single workshop incorporating the following Select and Create processes from the methodology:-

1. The Select Process: Assess process maturity.
2. Create Process: Decide Knowledge.
3. Create Process: Collate Knowledge.

Prior to each manufacturing evaluation, a short presentation lasting 5-10 minutes took place. This presentation introduced the methodology and the reasons for its use. However, it did not discuss any of the theoretical elements behind the methodology, such as the importance of the process maturity, the need for a different content and level of knowledge, the acknowledgement and consensus of the 'thought worlds' and the use of different knowledge types. Section 7.4 demonstrates how the evaluation surveys were designed to elicit responses to indicate the use of these elements. The output from each manufacturing evaluation session was recorded in a raw format in an Excel spreadsheet. As an example, the results to the first component evaluation (HP seal segment) can be seen in figures 7.1 – 7.3. Although actual manufacturing knowledge was recorded in the session, it cannot be displayed due to confidentiality.

7.3.2 Designers' Evaluation

The aim of this second activity was to evaluate the output from the manufacturing evaluation to determine its suitability for use in an initial manufacturing feasibility assessment. Consequently the output was considered an input to the 'Use' process. As the knowledge was evaluated by members of the preliminary design team, this represented the evaluation of the 'knowledge sharing' component of the methodology.

For each of the three cases, the output from the manufacturing evaluation session was presented as a 'form' – a MS PowerPoint presentation format with the aim of improving its presentation and to make it easier to read and use. As an example, figures 7.4 – 7.6 show the results for the first component (although again much of the knowledge actually captured cannot be displayed due to company confidentiality). For the actual designers' evaluation session, the knowledge was transferred word-for-word from the initial excel spreadsheets with no changes. The reason for this was that the presentation was a representation of a database form which would be displaying knowledge already recorded.

NORMANDYselect results

Engine Project: Data supplied

Component description	Sub-assy description	Material	New shape?	New material?	Process	Process type	Process maturity score
HP Seal segment		**Material C**	**Yes**	**No**	Core manufacture	Manufacturing	Mature
					Single crystal casting	Manufacturing	Mature
					Grinding	Manufacturing	Mature
					EDM	Manufacturing	Mature
					Brazing	Joining / assembly	Mature
					Milling	Manufacturing	Mature
					Sintering	Manufacturing	Mature
					Turning	Manufacturing	Mature
Honeycomb (feature)		Material C	Yes	Yes	DLD	Manufacturing	In development
Honeycomb (feature)		Material D	No	No	EDM	Manufacturing	Mature

Slight change to features compared to previous engine project.

Figure 7.1: Output from Select Process

NORMANDYcreate form

Manufacturing Process Level Constraints

Engine project	Name supplied
Component	HP seal segment honeycomb feature
Material	Material C / Material D

What are the historical, current and future (in development) methods of manufacture being considered?

Method of manufacture	Status	Maturity (from NORMANDYselect results)	Specialist contact	Additional notes
EDM	Current	Mature	Name supplied	
DLD	Future	In development	Name supplied	

Product Characteristics

Characteristic	Details	Value	Differentiating or influencing	Additional notes	Degree of confidence
Geometric	Abradable retention	Data supplied	Influencing	Data supplied	Data supplied
	Abradable retention	Data supplied	Differentiating	Data supplied	Data supplied
Material	Oxidation resistance	Data supplied	Influencing	Data supplied	Data supplied
	Crack resistance	Data supplied	Influencing	Data supplied	Data supplied
Other	Process cost per component	Data supplied	Influencing	Data supplied	Data supplied
	Existing capability	Data supplied	Differentiating	Data supplied	Data supplied
	Blade tip wear	Data supplied	Influencing	Data supplied	Data supplied
	IPR considerations	Data supplied	Influencing	Data supplied	Data supplied
	Environmental impact	Data supplied	Influencing	Data supplied	Data supplied

Figure 7.2: Output from Create Process

NORMANDYcreate form

Manufacturing Sub-process level constraints

Engine project: Name supplied
Component: HP seal segment (honeycomb)
Material: Material C
Process: EDM
Process maturity: Maturity

Machine differentiating characteristics

Characteristic	Details	Value	Differentiating or influencing	Additional notes	Degree of confidence
Geometric	Wall thickness tolerance				
	Surface finish				
	Parallel walls only				
	Node thickness				
	Pocket radii achievable				
Material	Temperature resistance				
	Oxidation resistance				
	Resistance to pick up				
Other					
Facility restriction	Capacity				
Facility restriction	Availability				
Production planning	Lead time estimate				
Costing	Unit cost per component				
Capability	Cp(primary)				
	Cpk				
	MCRL				

Figure 7.3: Output from Select Process

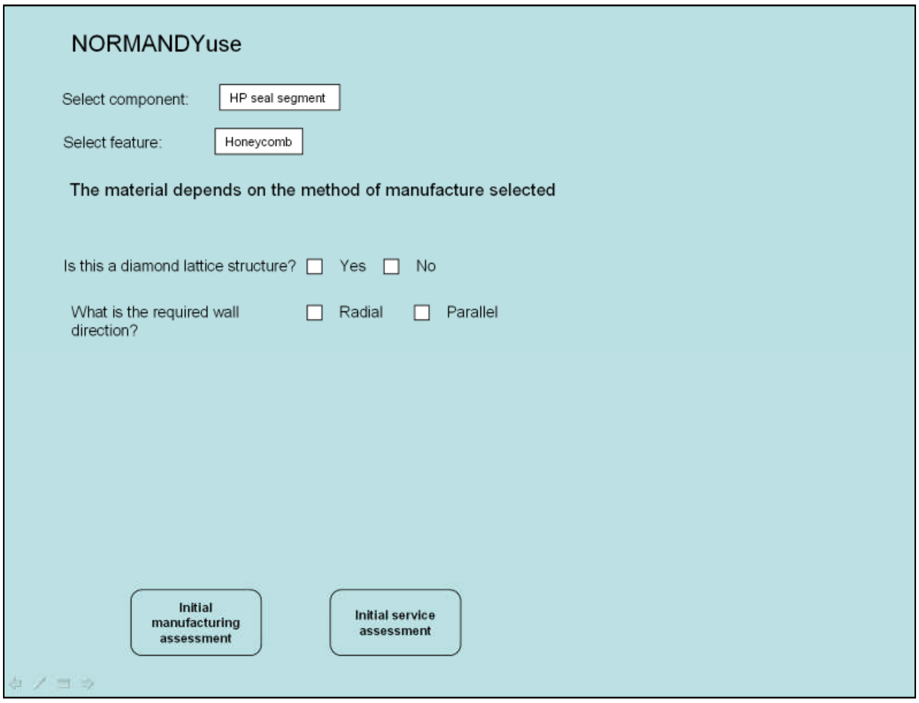


Figure 7.4: Designers' Evaluation form 1

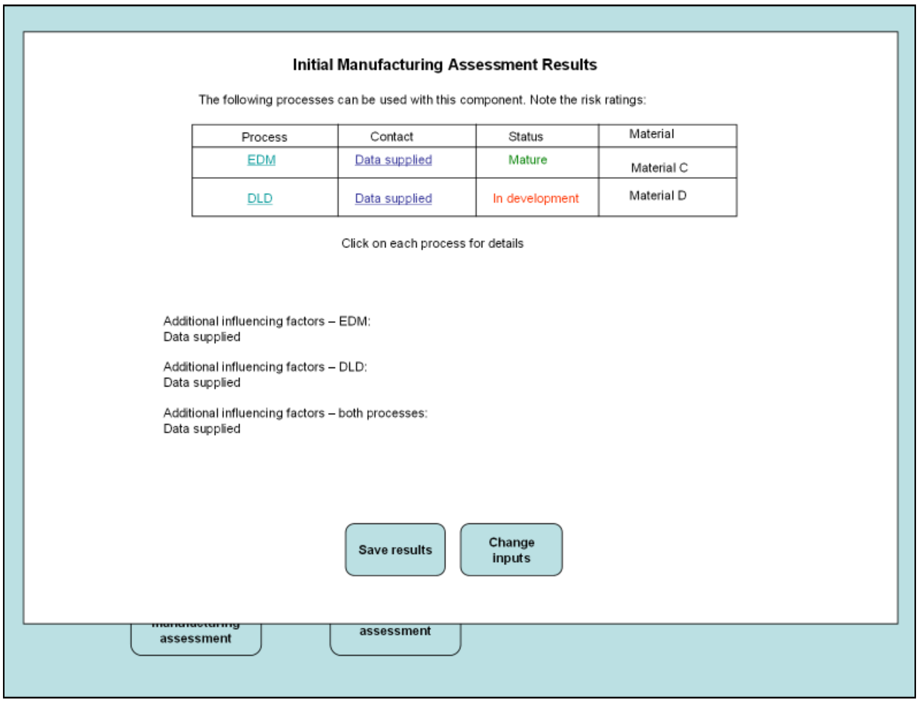


Figure 7.5: Designers' Evaluation form 1 (continued)

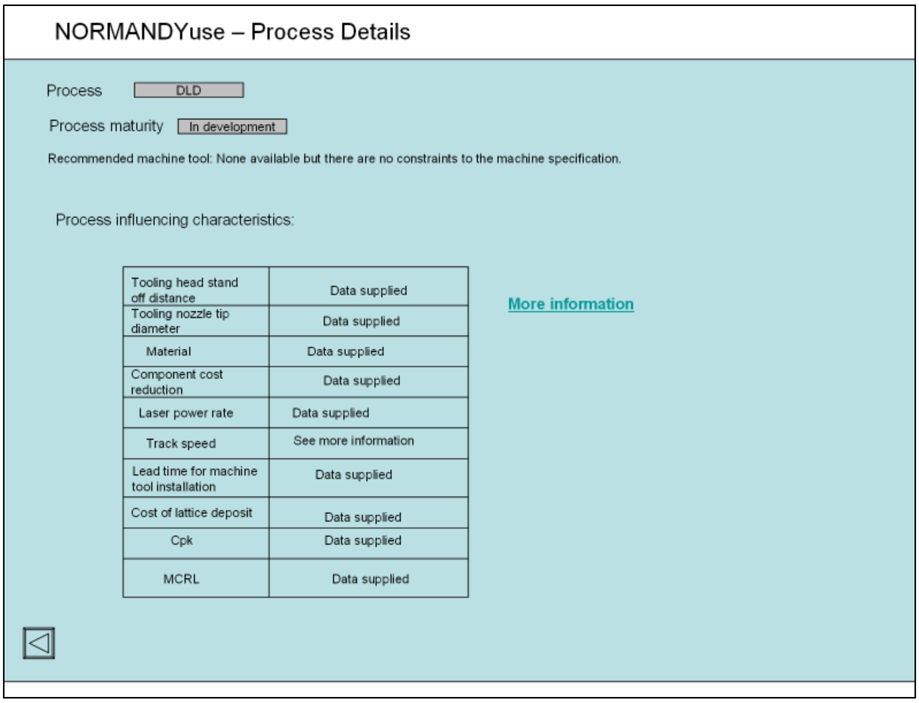


Figure 7.6: Designers' Evaluation form 1 (continued)

The format of each evaluation session again included a short introductory presentation with information about the methodology, its format, and use. As with the manufacturing evaluation, no information about the theoretical elements of the methodology was offered, yet the survey design ensured that the use of these was examined.

Two designers' evaluation sessions took place. In the first session the two forms representing the outcomes of the first two manufacturing evaluation sessions were presented. In the second session two forms were again presented. These both contained the knowledge captured in the third evaluation session. However, two views were presented of the same knowledge, with the second form deliberately less detailed.

7.3.3 Selection of Evaluation Session Participants

In order for the methodology to be effective and to recognise the need for sharing knowledge across the specialist domains, it was recognised that both design and manufacturing specialists would need to participate in the evaluation sessions.

The following candidates were therefore sought for each evaluation:-

Manufacturing Evaluation session:

- At least one manufacturing domain specialist for each process being considered.

- One design domain specialist with detail knowledge of the component design considerations (from the sub-systems division relevant to the component considered).
- One facilitator (to guide the workshop process and capture the output).

Designers' Evaluation session:

- A minimum of two preliminary mechanical design engineers with knowledge of the specific components considered in the manufacturing evaluation sessions.
- One facilitator.

In all cases, the role of the facilitator was taken by the researcher.

In order for the evaluation sessions to be successful, it was important to identify the most suitable candidates to take part. In this case, this referred to people with good detailed knowledge of the components / processes and their design considerations. Such people could be referred to as 'experts' although their individual age, experience and job history varied. In fact, those three factors were not considered in selecting the participants. The specialists were identified by the key stakeholders who had shaped to creation of the methodology as being the most suitable people to contact for those specific cases. The author notes that this is an example of the informal social network in action within the company, almost an unofficial 'peer review'. They were contacted and invited to take part. Responses were positive with the majority of invitees agreeing to take part with some degree of interest (and scepticism in some cases).

Identification of preliminary designers to take part in the Designers' Evaluation was more straightforward due to prior involvement with the department. That said, the same calibre of participants was sought, requiring experience of the design issues of the components used for each case. Because this knowledge is limited and the group is small, it was not possible to rule out the participation of designers who had been involved in previous stages of the research. However, some degree of time lapsed between the presentation of the interview results and the running of the evaluation sessions.

Again, as with previous data collection activities, all participants were assured of anonymity.

As each participant completed their own survey, the unit of analysis for the evaluation was initially each participant. Each participant was identified according to a specific number and evaluation session number. Comparisons were also made between evaluation cases and between domain specialists. The former were used to investigate the impact of changes in the methodology between each session and the latter to investigate perceptions of knowledge and knowledge sharing between domain specialists.

Tables 7.1 and 7.2 summarise the participants for each case.

Table 7.1: Evaluation Participants: Manufacturing Evaluations

Case	Participant
1. HP Seal Segment	1. Component Designer from sub-systems unit. 2. Manufacturing specialist, DLD 3. Manufacturing specialist, casting (Took part because this is the primary process for this product and participant had good understanding of associated design and manufacturing issues. 4 and 5. Manufacturing specialists, EDM
2. Compressor assembly stages	1. Component designer from sub-systems unit 2. Manufacturing specialist, EBW. 3. Manufacturing specialist, IW 4. Team leader, IW (left early).
3. Compressor case	1. Manufacturing specialist, forging and machining. 2. Manufacturing specialist, HIP.
Total participants	10

Table 7.2: Evaluation Participants: Designers' Evaluation

Case	Participants
1. HP Seal Segment 2. Compressor assembly stages (evaluated together)	1. Preliminary design team leader 2. Design capability manager 3 and 4. Preliminary mechanical designers.
3. Compressor case	1 and 2 Preliminary mechanical designers (same as previous session).
Total participants	6 (second evaluation considered as a separate case).

The evaluation sessions were designed to use these participants for two reasons. The first is that, as each participant was considered a domain expert, they were a rich and credible source of data. The second is that each participant could provide a viewpoint from each domain. These multiple viewpoints were also a source of data triangulation. Further triangulation was also provided by additional facilitator's observations which were noted during the evaluation sessions.

The three types of bias were also addressed. Researcher bias was reduced by ensuring that the participants completed the surveys individually and in their own words. Reactive bias was difficult to address as the researcher was an integral part of the evaluation session. Activities included identifying and recruiting participants, briefing them, facilitating the sessions and analysing the survey material. It is recognised that reactive bias may easily occur in the situation therefore the researcher attempted to keep an open mind to the investigations as far as possible. It was also difficult to address the possibility of respondent bias. The researcher attempted as far as possible to monitor for this by comparing the survey responses with comments made by and observations of the participants during the evaluation sessions. A situation occurred in Manufacturing Evaluation Session 1 where these did not match and therefore the survey was withdrawn from analysis.

7.4 Survey Design

As was seen in section 7.2.1, a series of ideal outcomes needed to be considered in evaluating the methodology. The survey would need to be designed to demonstrate if these outcomes had been achieved. Below is a list of six questions which relate directly to the ideal outcomes. Each question is designed to evaluate each part of the methodology against its original requirements:-

1. How useful is the manufacturing knowledge content collated in terms of carrying out an initial feasibility assessment in preliminary design?
2. How useful is the level of manufacturing knowledge collated in terms of carrying out an initial feasibility assessment in preliminary design?
3. Can the manufacturing process be expressed in different ways according to the process maturity?
4. Do the combinations of different knowledge types effectively express the process maturity?
5. Does a methodology with the features above present an effective way of knowledge sharing between the specialist domains of design and manufacturing?
6. Does the methodology enable an effective compilation of manufacturing knowledge?

This list of questions was then used to generate some initial ideas of the types of survey questions required to answer them. The results can be seen in table 7.3. These questions met one of two criteria:-

A. The effectiveness of the methodology in sharing manufacturing knowledge between designers and manufacturing engineers (i.e. validates the hypothesis).
B. Criteria which evaluate the effectiveness of the methodology design (i.e. validates the use of the methodology).

Many of the initial thoughts included some measure of ‘success’ with the methodology. Therefore a definition of ‘success’ for the methodology was required. Table 7.4 indicates what would be expected from the manufacturing and designer evaluation sessions if the methodology is said to be ‘successful’.

The survey therefore needed to elicit responses to rate the participants’ attitudes when compared to these indications of success. An attitude survey format was selected as being the most appropriate method of comparing the participants’ views of the success of the methodology against the indicators in table 7.4. Attempts were taken to keep each statement as neutral as possible to reduce potential bias in the wording of the survey.

Table 7.3: Initial ideas about question types

Question types	Reason	Criteria
Questions about what was specified using the manufacturing template / characteristics.	For an indication of how complete the required m/f knowledge is.	A
Questions about the level of info specified using the manufacturing template.	For an indication of whether the knowledge has been filtered, by how much it has been filtered and how appropriate this filtering has been.	A
Questions about recording the knowledge as quantified and comments in form.	To find out how easy it was for the specialists to work with the different knowledge types.	A
Questions about reading back the recorded knowledge and how it's recorded.	To find out how easy it was for the designers to use and interpret the knowledge.	A
Questions about whether using the methodology is a useful way of making a preliminary manufacturing assessment.	To find out if the designers and specialists found this useful. If so, why. If not, why not.	A
Whether the participants understood the requirements for each workshop process. Whether they found each workshop process easy to work through. Whether they found the workshops an effective use of time. Whether they found the workshops more effective than usual methods of working.	To find out if using the methodology was useful.	B

7.4.1 Survey Structure

Following from decisions of the survey type and type of questions to be included, the next part of the work was concerned with the structure of the survey itself: the questions to be asked at each part of the evaluation process, to whom these questions would be addressed and when the survey would be completed. Design of the survey structure ran concurrently with the design of the evaluation sessions (section 7.3). Two surveys were created. The first was designed to evaluate the Manufacturing Evaluation session and evaluate the manufacturing knowledge collected – from the point of view of the manufacturing domain specialists who had participated in the session. The second was designed to evaluate the Designers' Evaluation session and comment on the manufacturing knowledge presented back to the preliminary designers from their design domain specialist point of view.

In addition to the attitude survey questions, some additional open-ended questions were included in the survey to cater for more exploratory questions and to deal with the 'why' questions as well as the 'how'.

Table 7.4: Success indicators for each workshop process

Methodology Process	Indicators of success	Criteria
Manufacturing Evaluation: Select process	The participants are able to understand what is required.	B
	The participants are able to define the criteria.	B
	The participants are able to rate the process maturity for each manufacturing process.	B
	The participants view the process as being effective, efficient and straightforward.	B
	The workshop is useful in bringing together specialist domains.	A
	The risk-heavy components are identified in a quick yet effective way.	A
	The most relevant component / process combinations are recorded during the 'create' process.	A
Manufacturing Evaluation: Create process	The participants are able to understand what is required.	B
	Step 1 – Decide Knowledge	
	The participants are able to work through the template and define the constraints for the component / process combinations.	B
	The participants are able to categorise the constraints as qualitative and / or quantitative.	B
	The participants are able to define the range of information required for each constraint.	B
	The participants should agree that the knowledge requirements outlined as a consequence of the workshop are complete and suitable to fulfil the purpose of making an early manufacturability assessment. Any gaps in requirements should be noted as a continuous improvement exercise.	A A
	The workshop is a useful channel for cross-domain discussion.	B
	Step 2 – Record the values of the identified constraints	
	Defining and supplying the required knowledge should be (reasonably) straightforward.	B
	Templates for supporting semi-structured knowledge should be defined and completed.	B
	Links to expert contacts should be supplied.	B
	The manufacturing knowledge presented should be at a suitable range and level for use in preliminary design.	A
Designers' Evaluation	The manufacturing knowledge presented should be at a suitable range and level for use in preliminary design.	A
	The manufacturing knowledge should be genuinely useful in the design process.	A
	The process provides a collaborative forum in which designers and manufacturing engineers can work.	A
	The way in which the manufacturing knowledge is presented (using the combinations of different knowledge types) is useful in supplying the right amount of knowledge at the right level.	A

The initial layout for each survey is summarised as follows:-

Survey for Manufacturing Evaluation

Section A: participant information
Section B: Workshop 1 – the Select Process.
- Comments about the way the workshop ran.
- Comments about using the Process Maturity Audit.
Section C: Workshop 2 – Create: Decide Knowledge.
- Comments about the way the workshop ran.
- Comments about the manufacturing template.
Section D: Workshop 3 – Create: Collect Knowledge.
- About the way the workshop ran.
- Comments about completing the form.
Section E: Comments about the workshop and outcomes.
- Comments about the knowledge content defined.
- Comments about the knowledge level defined.
- Comments about the knowledge types.
- Part of the workshop which was most useful (open ended question).
- Part of the workshop which was least useful (open ended question).
- Other comments (open ended question).

Survey for Designers' Evaluation

Section A: participant information
Section B: Comments about the form
- Comments about the knowledge content defined.
- Comments about the knowledge level defined.
- Comments about the knowledge types.
Section D: General comments about the form
-Part of the form which was most useful (open ended question).
-Part of the form which was least useful (open ended question).
-Other comments (open ended question).

Some small changes were made to the survey between the pilot and evaluation sessions. The final version of the surveys for both the manufacturing specialists and designers are shown in Appendix E. Each question has an accompanying narrative in italics to explain the purpose of each question. These have been added for the thesis. They were not a feature of the surveys distributed to the workshop participants.

7.5 Pilot Evaluation Session

Once the formal evaluation sessions had been planned and designed, a pilot session was held to test the running of the evaluation session and initial results.

The pilot evaluation session ran for three hours (a morning session). The subject of the evaluation was a linear friction welded blisk. The two participants were a linear friction welding tool design specialist (for blisks) and a linear friction welding process specialist. Both specialists had been previously involved in the first blisk knowledge capture meeting.

The objective of the session was to use the methodology to carry out an initial process maturity audit of linear friction welding and to capture the relevant manufacturing knowledge relating to the blisk. In doing this, two things would be evaluated:-
1. The actual knowledge collected, especially when compared to the knowledge captured in the previous meeting. Was the methodology more effective?
2. How the evaluation session ran – the briefing session, timings, etc. – in order to make any final changes before the three evaluation sessions.

Observations from the workshop

The timings ran approximately as planned. The initial briefing ran well – in fact quicker than planned – and the information was presented clearly. There were no additional questions.

Select Process: the Process Maturity Audit

The pilot process maturity audit (PMA) was a series of questions, the answers to which were meant to determine the process maturity. It was found that the questions were ambiguous and open to too much interpretation. Following the session, the PMA was reworked into a list of applicable statements to remove the ambiguity. This was presented as the final version in this thesis. It was also noted that the term 'standardised' within the company applied to 'the way we've always done it' rather than a mature process where the process capability can be predetermined, therefore this required more clarification.

Create Processes: Decide and Capture Knowledge

No changes were made to the process – the manufacturing template content stayed fixed for the first main evaluation session (it was then changed between sessions 2 and 3). However, comments were received that the slides were 'too wordy', therefore the process was broken down into a further number of slides with less text to make the instructions clearer.

7.6 Manufacturing Evaluation Sessions

This section presents and analyses the results of the three manufacturing evaluation sessions. Section 7.6.1 discusses the observations made for each session, section 7.6.2 discusses the attitude scale survey answers and section 7.6.3 discusses the survey answers to the open-ended questions.

7.6.1 Observations

Evaluation Session 1 (HP Seal Segment)

The workshop lasted for four hours, plus an additional hour after the session to capture further knowledge for DLD process from the process specialist. The two EDM manufacturing specialists were involved by telephone conference call due to geographical restrictions. Unfortunately this hindered participation as they were unable to view the spreadsheet as it was being completed. Although both participants emailed the completed surveys it was difficult to gauge the credibility of the answers. One set of responses was excluded from analysis because it was a potential source of respondent bias - the author felt the answers to be formulaic and to be saying what the participant thought she wanted to hear rather than an objective appraisal of their actual experience. Consequently it was resolved not to include a telephone link call in any further evaluation sessions.

It was observed that individual manufacturing process specialists were very involved with their process to the extent that they could be protective. The researcher found this to be a surprise as it had been assumed (perhaps naively) that the resulting discussion would be objective and focussed on the technical benefits of different manufacturing technologies. This made the researcher consider whether it would be more appropriate to consider each process separately when using the methodology.

The results of the session were useful in determining the boundaries of where the use of the methodology was appropriate.

The participants found it difficult to quantify the values of knowledge they had specified. This may be because the knowledge was not yet mature. It may also be because the workshop was not the best forum in which to derive these values. It may be best to define the knowledge in the workshop but carry out the quantification (where appropriate) as a separate activity at a later date.

There was insufficient time to capture the process-specific information, therefore a follow-up session outside of the workshop with the DLD specialist was held to complete this.

The views from the specialists was that it was capturing everything it was intended to do, however an additional application was suggested – the demonstration of possible applications for new manufacturing technologies. Although out of scope with the methodology developed, it was an interesting viewpoint and also one which was also mentioned during the preliminary design evaluation sessions.

Changes made to the methodology after the session:

The main changes took place to the Create process. The manufacturing template was incorporated into the main process steps for further integration. The participants were asked to consider process characteristics but unlike the previous version, these were not asked as a series of set questions. These changes are highlighted in section 6.4.1.

Evaluation session 2 (Compressor stages)

There were initially four participants in this session, however the team leader had to leave after the first workshop (the 'select' process), therefore his survey responses were discounted. The workshop lasted for four hours, plus two additional hours after the session to capture further knowledge for both process.

Despite having a set workshop, there were a number of deviations from the required topic. The facilitator decided to allow this as she was interested to see what else was discussed, especially in terms of tacit knowledge transfer. The topics discussed were categorised as follows:-

- Discussions of viable current and potential future processes in addition to the two being compared in the workshop.
- Discussions about what suppliers have been doing.
- Discussions about assumptions about material selection and component design, new processes and how this can affect design requirements (for the better), process considerations, etc.
- Hypothetical discussions around what could be done with various processes (ref. G/A).
- Correction of 'hearsay' – the full story concerning supplier capability.
- Discussion on current design / process considerations on this and related components.
- Political issues ("which we shouldn't really be talking about").

As with the first session, the involvement of the manufacturing specialists with their particular processes was noted. The design specialist in particular appeared to gain some value in finding out about the processes, especially inertia welding where he had less experience (however his response in the survey indicated that manufacturing knowledge was something that he believed he would not use). Some misinterpretations and misconceptions were corrected.

The session appeared to be the smoothest running to date and appeared to be something where there was a benefit to the participants. However, the author's opinion was that it was still not running how she would ideally envisage it, yet it was difficult to pinpoint where changes were required.

Changes to the methodology after the session:

No changes were made to the methodology itself, however the author decided to invite a member of the preliminary design team to the next session to see if this would stream the information better for preliminary design use.

Evaluation Session 3 (Compressor case)

The preliminary design team were approached to see if they were interested in involvement but this was not possible at the time due to project constraints; a component design specialist was invited and accepted but did not attend on the day. The workshop lasted three hours.

This session was more focussed in adhering to the methodology therefore there was less ‘off topic discussion’. However, it appeared that much of the opportunity for this was lost with no designer being present.

There was a good suggestion for improving the methodology from one of the manufacturing specialists. He recommended that the session should be split into firstly focussing around the component and then the process characteristics.

7.6.2 Survey results: attitude scale questions

Tables 7.5 and 7.6 summarise the results of the attitude scale questions. The unit of analysis was initially each participant, however as can be seen the responses have been compared according to workshop attended and the domain specialism of each participant (design or manufacturing). Counts of attitude responses on the scale of 1 – 6 were taken. In most cases (unless shown in tables 7.5 and 7.6) this corresponds to 1: strongly disagree – 6: strongly agree, where a score of 3.5 would indicate a neutral response. In order to gain some idea of the consensus for each question, the mean score was taken. This was intended as a guideline rather than a rigorous statistical analysis, as this type which would have no meaning in the context of a qualitative analysis where a purposeful sample has been used. The analyses were taken using Microsoft Excel pivot tables.

In order to facilitate a discussion of the results the responses for each question have been grouped according to the reason for the question. These are now discussed in turn.

Questions concerning the Process Maturity Audit

The responses to this question were reasonable, indicating that perhaps some further development of this aspect of the methodology was required.

For both questions, the manufacturing specialists rated the process higher than the designers – 4.00 compared with 4.25 for B1 (both ‘slightly agree’) and 3.5 (‘neutral’) compared with 4.13 (‘slightly agree’) for B3. This may be because the language used to indicate the process maturity was written from the manufacturing point of view. However, only two surveys from design specialists were analysed compared to seven from the manufacturing specialists, therefore it is difficult to draw a definite conclusion based on this. A weakness with the survey was that an additional question about the usefulness of the process maturity audit was omitted. Therefore the only method of gauging this was from the open-ended questions in the survey.

Table 7.5: Survey results from the Manufacturing Evaluation Sessions

	Question	Overall average	Average by domain		Average by evaluation session		
			Design	Manufacturing	1	2	3
	Questions concerning the Process maturity Audit						
B1	I understood the statements in the audit	4.25	4.00	4.33	3.67	4.33	5.00
B2	The process maturity was assessed quickly	4.13	3.50	4.33	3.33	4.33	5.00
	Questions concerning knowledge content and level						
C1	I was able to identify the manufacturing characteristics	3.86	3.50	3.86	4.00	3.00	4.50
C2	Identifying the characteristics was easy to work through	4.00	4.00	4.00	3.75	4.33	4.00
C3	Identifying the characteristics was quick to work through	3.56	3.50	3.57	3.50	3.00	4.50
C4	It was useful to distinguish between differentiating and influencing characteristics	4.44	4.50	4.43	4.00	5.00	4.50
C5	Following the template was more effective than group discussions	4.00	4.00	4.00	4.75	3.33	3.50
D1	I could identify the knowledge required	4.11	4.00	4.14	4.00	4.00	4.50
E1	The content of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design	3.56	3.50	3.57	3.75	3.67	3.00
E2	The level of detail of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design	3.44	3.00	3.57	4.00	3.00	3.00
E3	Compared to the manufacturing knowledge I would use in my job role, the recorded knowledge is (1 much less detailed – 6 much more detailed)	3.25	4.00	3.14	3.50	3.00	3.00

Table 7.6: Survey results from the Manufacturing Evaluation Sessions (continued)

	Question	Overall average	Average by domain		Average by evaluation session		
			Design	Manufacturing	1	2	3
	Questions about the use of different knowledge types						
D2a	Recording the manufacturing knowledge as numerical information was (1 not at all useful – 6 very useful)	3.22	3.50	3.14	4.00	3.00	3.22
D2b	Recording the manufacturing knowledge as numerical information was (1 too time consuming – 6 an effective use of time)	2.78	3.00	2.71	3.25	3.00	1.50
D3a	Recording knowledge as additional comments was (1 not at all useful – 6 very useful)	4.67	4.00	4.86	4.50	4.67	5.00
D3b	Recording knowledge as additional comments was (1 too time consuming – 6 an effective use of time)	4.33	4.00	4.43	4,50	3.67	5.00
D4a	Being able to discuss the manufacturing knowledge requirements in a workshop setting was (1 not at all useful – 6 very useful)	5.11	5.00	5.14	5.00	5.00	5.50
D4b	Being able to discuss the manufacturing knowledge requirements in a workshop setting was (1 too time consuming – 6 an effective use of time)	4.11	4.50	4.00	4.50	4.00	3.50
E4	It was useful to be able to combine recording numerical and text knowledge in the same form (1 strongly disagree – strongly agree)	3.78	4.50	3.57	3.75	4.33	3.00
E5	It was useful to be able to combine recording knowledge (as text and numerics) and workshop discussions (1 strongly disagree – 6 strongly agree)	4.56	5.00	4.43	4.25	5.00	4.50

Questions concerning the knowledge content and level

These questions examined the following aspects of compiling the manufacturing knowledge: whether the methodology could be followed easily, whether there was a benefit in using it and whether the knowledge identified was applicable and suitable for an initial feasibility assessment.

Questions C1, C2, C3 and C5 were concerned with the use of the methodology itself. For C1, the response was largely neutral (3.78), indicating that further work may be required to improve the definition of the knowledge content. Answers were consistent between the design and manufacturing domains, however there were some fluctuations between workshop sessions. In terms of the ease of working through the methodology, the response to C2 was a ‘slightly agree’. This is consistent between the design and manufacturing domains (both 4.00) yet fluctuates between workshop sessions. The change in format between workshops 1 and 2 may account for the change in scores (although it drops on content).
The reply to C3 (the speed to work through the process) is neutral.
Question C5 is an important question because it compares the use of the methodology with normal working practices. The consensus appears to be ‘slightly agree’ although this does vary between workshops.
The responses to the questions indicate that further work would be required to develop the methodology for practical use.

Questions C4, D1, E1, E2 and E3 address the more fundamental question of whether the methodology effectively met the requirements it was designed to address. Question C4 consistently scored on the ‘slightly agree’ scale for all average responses, indicating the differentiating and influencing characteristics definitely appeared to be useful. The response to D1 – identifying the knowledge – again scored ‘slightly agree’ for all responses. E1 and E2 scored mainly ‘neutral’ with some ‘slight disagreements’ indicating that despite identifying knowledge, the methodology was not identifying everything required to carry out its purpose. The answer to E3 was aimed at comparing the level of knowledge required for different domains. If preliminary design knowledge is at a more abstract level than that with which manufacturing specialists would be expected to work, then some disagreement would be expected with this answer. Responses ranged from slightly agree to slightly disagree, possibly indicating that this had not been successful.

To summarise, given that there was no strong opinions of disagreement with the methodology, one could say that it is successfully addressing some of the requirements but requires further refinement.

Questions about the use of different knowledge types

Questions D2a and b are about the use of structured knowledge in the workshop. They score the two lowest scores of the survey. The scores for questions D3a and b – about the use of semi-structured knowledge improve significantly. The score of 4.67 for question D3a is the second-highest score in the survey. The answer for D4a – about the use of unstructured knowledge (in the form of workshop discussions) is the highest score in the survey at 5.11. Question D4b, about the effective use of time knowledge sharing of this type scores 4.11. There appears to be some ambivalence about its use.

Question E4 concerned the use of explicit knowledge, defined here as the combination of structured and semi-structured knowledge. Overall the response appeared to be neutral. Question E5 concerned the use of both the explicit and tacit knowledge in the methodology. This scored overall 4.56, the third highest score in the survey.

7.6.3 Coded Responses to Open-ended questions

For the open-ended questions, the answers to each question were analysed to investigate common themes. The themes were then categorised into general codes. This was effectively an open coding exercise, similar to that seen in the analysis of the data collections.

E6. What was the most useful part of the workshop for you and why?

Knowledge sharing: 5
Knowledge content: 1
Manufacturing impact: 1
Process maturity: 1
Not answered: 1

The ‘knowledge sharing’ responses can be further categorised:-

Sharing of m/f knowledge between different domains: 2
Clarification of manufacturing knowledge: 1
Understanding others’ thought processes: 1
Review and revision: 1

The categories identified were consistent with those identified in the conceptual framework and framework of questions. The attempt at sharing knowledge across different specialist domains was also recognised.

E7. What was the least useful part of the workshop for you and why?

Structured knowledge: 3
Process maturity: 1
Time required to run: 1
Scope of the methodology: 1
Nothing specific: 1
Not answered: 2

Six answers were provided which could be analysed. The scope of the methodology and timing were related to small amendments of the methodology content and timing. The structured knowledge was interesting, with comments that it was difficult to identify, valuate and verify. This may be due to the developmental nature of the process. Process maturity was also listed by one participant (a designer), although this could be because they already knew about it and did not see its relevance to them in the workshop.

E8 What changes would you recommend to the methodology and why?

Terminology: 3
Methodology design: 2
Methodology content: 1
Usability: 1
Not answered: 2

The responses to this question appear to support the findings from the survey – that the methodology is a 'step in the right direction' but developments are required.

E9 Would you be interested in using any aspect of this methodology in your job role?

Yes: 5
No: 2
Don't know: 1
Not answered: 1

'Yes' responses:-
Systematic approach: 3
Design / m/f interface: 1
Business case: 1

'No' responses:-
Already have tools: 1
No reason given: 1

'Don't know' responses:-
Would want another trial: 1

The reasons for using the methodology appear to match some of the original aims of the research and the initial generated requirements. There also appears to be some benefit found with the use of a systematic approach to sharing knowledge.

7.7 Designers' Evaluation Sessions

This section presents and analyses the results of the two designers' evaluation sessions in a similar format to section 7.6. Section 7.7.1 discusses the observations made for each session, section 7.7.2 discusses the attitude scale survey answers and section 7.7.3 discusses the survey answers to the open-ended questions.

7.7.1 Observations

Designers' Evaluation Session 1 (HP seal segment and compressor assembly stages)

This first evaluation session considered the results of the first two manufacturing evaluation sessions. It was deliberately held before the final manufacturing evaluation so that any further changes could be made to the methodology if required. The following concerns were raised:

- The content and level of manufacturing knowledge displayed was far too detailed for an assessment at stage 1.
- There was some debate over the component level at which the methodology should be aimed. The second form, featuring the compressor assembly was more useful than the first, which was a detailed manufacturing feature (the seal segment).
- There were concerns over the resources and time required to firstly compile the knowledge and then keep it updated. This would detract them from using it.
- There were concerns over how this methodology could actually be used and the benefits to be gained from it.

There were some good points:

- There was genuine interest in the manufacturing knowledge displayed.
- There were attempts to see how this could be applied to their situation. There were, for example, thoughts that this could be useful as a database for new manufacturing engineers.
- They were open to the consideration of using new manufacturing processes as a means of investigating new shapes for components.
- They liked the combination of manufacturing knowledge and process maturity (MCRL).

Feedback between evaluation sessions

Following the first evaluation session, a feedback discussion took place with the preliminary design team leader, who was one of the evaluators in the first session. The aim of the session was to discuss the requirements further. The following were generated as a consequence of the discussion:-

- Any links to life and performance.
- Material limitations (where possible).
- MCRL
- Anything that affects component sizing.

Two forms were produced for the final evaluation session. Both were an output from Manufacturing Evaluation 3. The second form was modified to remove any additional manufacturing detailed knowledge which did not relate directly to the requirements listed.

A preliminary designer was invited to the final evaluation session to see if this would have an additional effect on the content and level of manufacturing knowledge generated. Unfortunately they were unable to participate.

Designers' Evaluation Session 2 (compressor case)

There were some concerns over the accuracy of some of the claims made in the manufacturing knowledge with the opinion raised that some independent validation would be required for recorded knowledge. The approach that would be relevant for preliminary design was to show the knowledge at the functional / generic component level, a method of exploring different combinations of materials and methods for generic components. Preliminary designers are not interested in manufacturing knowledge at the feature level.

In both designer evaluation sessions and the feedback session in between, requirements and perceptions of requirements appeared to be based on the then current preliminary design process.

7.7.2 Survey results: attitude scale

Initially the surveys were analysed according to participant. They have been grouped together and compared by case. For each case, one form was presented, except for forms 3 and 4 which are two versions for the same case. Form 4 contained essentially the same knowledge as form 3, but with the content and level slightly amended to be more in line with the perceived requirements of preliminary design.

There is a significant difference in the mean scores between forms 1 and 2 and forms 3 and 4. This may be due to two additional evaluators being present in the first session.

As with the manufacturing evaluation results, the answers are indicated on a scale of 1 – 6 where 1: strongly disagree and 6: strongly agree (unless otherwise stated in table 7.7). The same method of analysis has also been applied, taking the average score for each question as an indicator of opinion rather than a statistical result. Again the results were compiled using pivot tables in MS Excel.

Table 7.7: Survey results for Designers' Evaluation

	Question	Overall average	Average by form number			
			1 (HP Seal segment)	2 (Compressor assembly)	3 (Compressor case version 1)	4 (Compressor case version 2)
	Questions concerning the knowledge content and level					
B1	The content of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design	3.00	2.25	2.75	4.00	4.00
B2	The level of detail of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design	3.17	2.75	2.75	4.00	4.00
B3	Compared to the manufacturing knowledge I would use in my job role, the recorded knowledge is (1 much less detailed – 6 much more detailed)	4.67	4.75	4.25	5.00	5.00
B5	The form distinguishes between knowledge which constrains manufacturing process selection and knowledge which is background for a business case	3.88	4.00	3.75	not answered	not answered
B6	It is useful to distinguish between knowledge which constrains manufacturing process selection and knowledge which is background for a business case	5.71	5.75	5.67	not answered	not answered
	Question about the use of different knowledge types					
B4	It is useful to have numerical and text knowledge and contact details for specialists combined in the same form	5.42	5.25	5.50	5.50	5.50

Questions concerning the knowledge content and level

For questions B1 and B2, there is slight disagreement overall with the ability of the knowledge content and level in providing knowledge to perform an initial feasibility assessment. The reason for this may perhaps lie in the responses to question B3. The knowledge accumulated is more than 'slightly more detailed' for their perceived requirements. Despite amendments being made between forms 3 and 4 to cater for this, this does not affect the overall scores.

In terms of distinguishing between constraints and business case knowledge (called differentiating and influencing characteristics in the Create process of the methodology), the opinion as to whether this is achieved is neutral (3.88). However, this was rated very highly (5.71) as a requirement for the knowledge.

Questions about the use of different knowledge types

The purpose of this question was to enquire about the use of both explicit and tacit knowledge. The explicit knowledge – structured and semi-structured – is provided by way of the output form. The form itself cannot supply tacit knowledge, however the named contact in the form provides a link to a network of experts for tacit knowledge transfer if so required. This scored very highly in agreement.

7.7.3 Coded Responses to Open-ended questions

Again, an open-coding approach was taken to the results in that similar answers were grouped together under common themes. There are more categorised answers than number of participants because some participants listed more than one answer to each question.

D1. What was the most useful part of the form for you?
Responses:-
Knowledge content: 3
Process maturity: 2
Manufacturing impact: 2
'Useability': 1
Additional contact links (unstructured knowledge): 1

Despite concerns as to whether the knowledge was supplied at the 'correct' content and level, it was rated as useful by three respondents. The indication of process maturity was rated by two participants which was interesting as this was not explicitly covered in the attitude response questions. The demonstration of manufacturing impact was also listed by two respondents. These responses tie back to the original model of requirements, so demonstrates that these are useful to both designers and manufacturing specialists. The ease of use of the output form was also mentioned.

D2. What was the least useful part of the form for you?
Responses:-
Content not appropriate to preliminary design: 1
Issues with resources to keep database updated: 1
Duplication of knowledge in existing R-R systems: 1
No perceived advantage for preliminary design: 1
Info on standard process info: 1
Accuracy of knowledge: 1
Not answered /specified: 2

Some of the responses show concern with the methodology itself – the content it defines and the advantage of this. Standard process information is not considered to be useful because it is well defined elsewhere. Because the methodology was developed in isolation there are concerns that it duplicates knowledge in existing systems. There were other concerns about the accuracy of knowledge, how it would be updated and who would take responsibility for this. Many of these concerns can be addressed with future development work, however some, such as the requirement for a methodology of this type, are more fundamental. It is noted that the view of the benefit / use appears to come from the perception of what is required from the preliminary design team at the moment (i.e. their thought world).

D3. What changes would you recommend to the form? Why?

Business readiness: 1
Methodology scope: 5

Breakdown of methodology scope:-
Knowledge other than manufacturing: 1
Process knowledge: 1
Focussed around preliminary design: 1
Application to generic component families rather than specific component families: 1
Link to existing systems / knowledge: 1

The 'business readiness' response recognises that further development within the business would be required to prepare the methodology for practical use. The remaining responses are concerned with the scope of the system – that it should be focussed more towards preliminary design and that the knowledge should be more generic at this stage. This could take two forms: either generic process knowledge which could then be investigated as potentially new manufacturing solutions, or linking the manufacturing knowledge at a higher, generic component level rather than linking to actual project components. Both of these would enable more investigative work to be undertaken before a project commences. Perhaps the requirement should be before stage 1 design. Other comments would be to see a methodology such as this expanded to disciplines other than manufacturing and a better link to existing systems and knowledge.

D4 Would you be interested in using any aspect of this form in your job role?
Yes: 3
No: 0
Don't know: 3

Yes responses:-

For specialised components which directly influence engine architecture: 1
As a prompt for discussions with a specialist: 1
For generic knowledge about new processes: 1

Don't know responses:-
Not sure it's what I need: 2
Don't see how it relates to a conversation with an expert: 1

These comments again support earlier responses. The first concerns the components which require the most input from preliminary design. The second supports the tacit knowledge transfer requirement (although in the 'don't know' responses one respondent is not sure about this). Others are not so sure of the requirements with another urging a more generic approach.

D6. Any other comments?
Two concerns about keeping the spreadsheet updated.

7.8 Combined Survey Responses

Five questions in each survey were designed to enquire about the same phenomena, although in some cases the wording used was slightly different. The manufacturing responses and preliminary design feedback responses were therefore compared. The similar questions have been called questions 1, 2, 3 and 4. The key is as follows:-

Questions concerning the knowledge content and level

The response for questions 1 and 2 is slightly disagree. The response for question 3 demonstrates the difference in requirements for both specialist domains. For manufacturing engineers the response is 'slightly less detailed', however this is still too much detail for preliminary design. Ideally the 'correct' response for this would be neutral for the preliminary designers. Both domains are in some degree of agreement – preliminary design especially – with question 4 and the need to differentiate between different types of knowledge and its potential use. However, the designers' overall opinion was that this wasn't really achieved (ref. q B5/B6) so this indicates another area where the methodology should be improved.

Table 7.8: Combined survey responses

	Question	Overall average	Average by evaluation session	
			Manufacturing	Design
	Questions concerning the knowledge content and level			
1	The content of manufacturing knowledge is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design.	3.24	3.56	3.00
2	The level of detail of manufacturing knowledge is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design.	3.29	3.44	3.17
3	Compared to the manufacturing knowledge I would use in my job role, the knowledge recorded is (1 much less detailed – 6 much more detailed)	4.10	3.25	4.67
4	It is useful to distinguish between knowledge which constrains the manufacturing process and knowledge for a business case	5.00	4.44	5.71
	Questions concerning knowledge types			
5	Usefulness of combining numerics, text and workshop sessions (additional contact details)	5.05	4.56	5.42

Questions concerning knowledge types

There were differing levels of agreement to question 5 with the prelim designers rating it more highly. Overall the reply was 'agree'.

7.9 Key Observations

It is evident that differences do exist between the appropriate levels of manufacturing knowledge for the two specialist domains who participated in the evaluation sessions. It appears that the appropriate level is unknown to the domain members themselves, especially in preliminary design. The knowledge appears to be very subjective in that sense. It appears to be very challenging to find the most appropriate level of granularity of the knowledge. Furthermore, the knowledge required appears to vary depending on stage of the design process, the required manufacturing assessment required at that stage and perceptions of the knowledge required at that stage. If the process is altered in any way then the required manufacturing knowledge required is also altered. It is possible that the different 'thought worlds' are created by the segregation of activities and job roles according to the stages of the design process.

There appears to be evidence that the methodology achieved some success in bringing together the requirements of both domains in a systematic way. However, it is also evident that further work is required in order to investigate the granularity of knowledge that is required. This appears to be an iterative and refining activity. A pre-requisite to this work would be another iterative definition of manufacturing knowledge requirements for preliminary design. This became evident from the evaluation sessions with preliminary design. It seemed apparent that this had been a first attempt to define manufacturing knowledge for preliminary design. The value that the designers derived from the session appeared to be not so much the actual evaluation form, but more that the session had acted as a catalyst to generating ideas and thoughts on the nature of manufacturing knowledge for preliminary design. The sessions in this respect were useful in generating such ideas. However, in isolation these requirements would be very much in line with the preliminary design specialist domain. The knowledge content needs to be defined across domains.

The effect of political issues was not considered during the design of the methodology and consequently came as a surprise during the evaluation sessions. It is clear that this may need to be considered if the methodology is defined further. However, the aim of the methodology in providing an objective technical comparison of processes must not be diluted.

The process maturity element of manufacturing definition definitely appears to have an advantage for two reasons. Firstly, it is a valid method of showing inherent risk in process selection. Secondly, as hypothesised, it governs the extent to which knowledge can be quantified and the appropriate types of knowledge to be used. This became apparent from the ratings of different knowledge types for processes 'in development'. Structured knowledge was rated the lowest because it was difficult to quantify certain aspects of the processes. Semi and unstructured knowledge were rated as being more useful.

The evaluation sessions have therefore partially validated the requirements for a methodology for sharing manufacturing knowledge. Process maturity is important and governs the way manufacturing knowledge should be expressed. Different knowledge types are required for this, both tacit and explicit. The knowledge level and content definitely needs to be at a more generalised and abstract level for preliminary design, with further investigation required into granularity.

These results appear to support and validate the conceptual framework and the need to explore the knowledge-sharing aspects of the preliminary design process. One could question whether the need for tacit knowledge sharing would be required as much if the knowledge requirements were better defined. It is suggested that it is this uncertainty drives the requirement for tacit knowledge exchange.

However the evaluation does illustrate the importance of the manufacturing impact (on size and shape), importance of process maturity, and requirements of different knowledge types in the preliminary stage. Consequently these results can be used to shape future knowledge management strategy for this area.

7.10 Summary

The methodology developed in chapter 6 was evaluated by a single embedded case study. Its use was trialled using three cases of different combinations of components and manufacturing processes. Each case was deliberately selected as an example of purposeful sampling. Each evaluation session was observed and a qualitative survey completed by each participant to gauge the success of the methodology in sharing manufacturing knowledge effectively.

The results of each session were then fed back to and evaluated by the preliminary design team, to investigate if the appropriate knowledge requirements had been identified and collated. Again, qualitative surveys were used in the evaluation.

The findings identified that there was some success in the methodology in enabling knowledge to be identified and shared appropriately, thus confirming the earlier hypothesis of manufacturing requirements. However, further work was required to develop the methodology into a practical format which could be applied in an organisational setting.

Chapter 8

Discussions, Conclusions and Future Work

8.1 Introduction

Previous chapters have recorded the development and testing of a hypothesis which outlines the manufacturing knowledge requirements for preliminary design and how they can be shared effectively between designers and manufacturing engineers. This hypothesis was derived from two interpretive data collection activities, the first of which generated a conceptual framework of manufacturing knowledge requirements and the second which highlighted how knowledge requirements need to be generated from and shared across different specialist domains for specific components and processes. A methodology was then created which embodied these requirements as a means of testing the hypothesis which was then evaluated using a sub-assembly, a component and a feature.

This chapter draws together and discusses the conclusions from each stage of the study. A number of factors need consideration in its conclusion. The research design approach and strategies used are appraised and the limitations of the study are considered. The practicalities of the resulting methodology are considered. The conclusions of the study and contributions to knowledge from this work are then highlighted and opportunities for further research work discussed.

8.2 Discussion of the Research Design and Strategy Approaches

The aim of this study was to examine manufacturing knowledge in a real-life study of complex mechanical components and the problems encountered in sharing this knowledge between different specialist departments. The main method of knowledge sharing was by human interaction for the benefit of a number of different domain specialists. In practice it was found that the knowledge was often messy, incomplete or difficult to define. Consequently an approach to the research design was required which would account for this. A flexible design approach was used with specific exploratory strategies for each research objective. This approach and the strategies require evaluation.

8.2.1 Comments about the use of a flexible design approach

As discussed in chapter 3, the selection of the research design and strategy approach was based on the exploratory nature of the first research question as there was no pre-existing theory or model on which to frame the enquiry. As the study progressed, subsequent research questions emerged from the results of the previous section of work. This enabled a fully flexible approach to be taken to the study. However, typically each section of work created more questions than answers and it took time to decide the most effective approach and research question for the next section. This resulted in some work being started and then abandoned to better orientate the research objectives. However, there were also definite benefits in the approach as the author was in a better position to react to the results from an activity which were unforeseen but formed an important part of the findings. An example of this is the data collection activity for the second research activity. It was originally assumed that this would be a straightforward technical data collection activity, however the effect of the different specialist domains emerged as a critical aspect of the study.

8.2.2 Comments about the approach adopted for research objectives 1 and 2

Research objectives 1 and 2 constituted the inductive part of the study. In both objectives, a hypothesis emerged from the analysis of qualitative data. Research objective 1 used the grounded theory techniques of open, axial and selective coding for analysis. For the second objective open coding (categorisation into different themes) was mainly used to classify data collected through ad-hoc discussions. It was found that there were strengths and weaknesses in using this approach.

In terms of strengths, the approach adopted appeared to be very effective for collecting knowledge about critical cases where such a theory does not currently exist. This was due to the method used for coding. This was a rigorous line-by-line examination of interview transcripts. There was evidence of triangulation because examples of the emergent themes could be seen across the responses. This was later confirmed with the feedback session held with the interviewees. The analysis was based on recorded data and was not reliant purely on the interviewer's notes and memory, which may have been incomplete or prone to research bias.

The main weakness in adopting a data-driven approach is that there is a risk of describing known phenomena and not contributing anything new. This was certainly the case with research question 1. It is acknowledged that some of the themes which emerged from the data analysis were not novel. These were the relationship between component, material and manufacturing process, expressions of tacit and explicit knowledge and the link between the codification of knowledge and the maturity of knowledge and process. All these themes were previously reviewed in chapter 2. It is therefore suggested that the contribution to knowledge from the hypothesis creation is twofold. Firstly, because the themes emerged independently from other research work from the coding process, it is suggested that the analysis work acts as a consolidation (or triangulation) of the previous research work. Secondly, the creation of the conceptual framework demonstrated how these previously unrelated themes connect for the definition of manufacturing knowledge for preliminary design for the specific case in consideration. The hypothesis also added process maturity as required knowledge content for preliminary design in addition to method, capability and cost.

The conceptual framework developed from the first research question formed the foundation of the requirements for the methodology. However, this model itself was abstract as the aim of grounded theory is to create a generalised theory to describe a range of situations. Although the responses were valuable in forming the model, it became apparent that further investigation was needed into a specific component in order to produce some tangible evidence of the manufacturing knowledge.

The second research objective was therefore formulated to carry out this investigation, with the expectation that a neat set of technical requirements would be generated. The results yielded not only the manufacturing knowledge required but also the problems encountered in sharing this knowledge due to the different 'thought worlds' within the domain specialties. The data collection involved in reaching these conclusions was less formalised than for research objective 1 and involved a series of ad-hoc unstructured discussion with a series of specialists in different departments. As with research objective 1, this approach had strengths and weaknesses.

In terms of strengths, the ad-hoc approach was pivotal in providing evidence of the different 'thought worlds'. As each discussion was unstructured it became led by the specialist's knowledge and allowed a recording of their specific knowledge sharing requirements and problems. Indeed, the 'thought worlds' result took some time to emerge, with the researcher's initial thoughts being, "Why is everybody telling me something different?" during the discussions. The 'thought world' phenomena therefore emerged from the analysis of the notes recorded.

However, it is acknowledged that the ad-hoc and informal nature of this data collection made it vulnerable to respondent bias. Also, despite the intentions of the researcher to remain impartial and take complete notes, there may have been some degree of researcher bias, i.e. in selective note taking and by prioritising issues which were in line with their own inherent experience and views. However, this may have been mitigated in that many of the issues encountered were of a technical nature, were therefore factual and not open to interpretation (although the reason for their occurrence may be).

Overall, the strength of the approach for this objective outweighed its weakness in terms of the resulting data analysis. Indeed, it could be argued that some degree of respondent bias was necessary in order to show evidence of the differing requirements of the thought worlds. However, this could have been better mitigated by a more rigorous approach to questioning and a method of recording other than by researcher notes.

8.2.3 Comments about the approach adopted for research questions 3 and 4.

Research questions 3 and 4 constituted the hypothesis testing part of the study. During research objective 3, a methodology was created to test the hypothesis generated during the first half of the study. Consequently, no new data was collected for this phase of the work, however the conclusions from the objectives 1 and 2 were the basis for the creation of the methodology.

The methodology emerged from the analysis of the data collected during phases 1 and 2. Therefore, once again it conformed to a flexible, data-driven qualitative design. A set of systematic processes were then designed around the two parts of the methodology (the process maturity audit and the characteristics) to create a series of logical steps which could be realised in a workshop format. These also formed the basis of a series of requirements for an ICT support system which were envisaged as an interactive intranet site linked to a database for recording the knowledge.

Feedback from the key stakeholders was very important during this stage as a peer debriefing / support activity to reduce researcher bias. The use of several stakeholders at various stages of the design process was also effective in triangulating the methodology requirements and hence reducing researcher bias.

The focus of this objective was on creating processes for identifying, collating and sharing knowledge. This resulted in two processes – the 'Use' and 'Review' processes – being deemed out of scope for completion. This is a weakness in this objective, as it would have been useful to work these through to check viability of the methodology proposed. It may also have allayed some of the issues concerned with maintenance and support which were noted during the evaluation session.

The final research objective was an evaluation of the methodology creating during research objective 3. Use a single-case embedded case study, three components were evaluated using the methodology. The components were critical cases in that they were deliberately selected to be relevant to the methodology. The processes were examined at assembly, component and feature level respectively and this proved to be a useful differentiator for the preliminary designers' feedback.

The analysis was qualitative, using a survey with a combination of attitude scale and open-ended questions and additional observations to triangulate the survey results.

The limitations in the attitude scales questions were frustrating in that they provided a measure of the participant's reaction but not the reasons for this. On a scale of 1-6 the majority of replies were in the 3-4 range which meant that many results were inconclusive. The open-ended questions were found to be far more useful in generating responses and a more effective addition to the attitude scale questions.

The observations were useful in interpreting the survey results as the responses could be compared with participants' attitudes during the workshop session. However, more formalised methods of recording and analysing the observations would have added additional rigour to this process.

A further unfortunate but major weakness in the evaluation was the involvement from the preliminary design team. The involvement of more of the group would have been useful from two perspectives: evaluation of the output of the workshops and participation in the workshops. The latter would have been very useful particularly for evaluating tacit knowledge transfer between all the domain specialists.

8.2.4 Discussion of alternative approaches

The strength of this research study is that it was able to expose and examine the finer details and complexities of defining and sharing the knowledge. It is the author's opinion that the research approach adopted was instrumental in achieving this. There are certainly different ways in which this research problem could have been approached. However, it is important to note that this would have completely changed the enquiry. Some examples of possible alternative approaches follow.

Rather than accounting for the different 'thought worlds' of the domain specialists, a more fixed approach could have been used. An ontology of preliminary manufacturing knowledge could have been developed as an initial model and tested on several components to see if this was a fit for the 'real world'. In a way, this was the original purpose of capturing the blisk knowledge. It was through this work that the researcher experienced in practice the way in which data can be 'messy' and pertaining to that thought world. The developed methodology could perhaps be interpreted as an initial attempt to bring the thought worlds together to create such an ontology. Approaching the problem as a test of an initial model may have given better initial guidance to the study, however the 'messiness' and complexity experienced in this project may have been missed.

In chapter 2, a comparison was made to the two different approaches taken by research in this area – as a method of supporting the specialists or by automating the process. This project adopted the former approach. In attempting to develop a tool to automate the process the same issues of maturity of process and (more importantly) the knowledge relating to that process may have arisen (for an example of this see (Haque et al., 2000)). However, problems may have been encountered in attempting to standardise and automate knowledge which cannot be standardised and automated. Attempting this problem using this approach would be an interesting exercise.

A flexible approach to the study could have been used with the emphasis on different parts of the problem. Research objectives 1 and 2 could have been expanded to include other organisations responsible for complex mechanical components to increase the external generalisability of the study. However this would have again changed the focus of the study to become purely inductive. Further evaluation of the hypothesis would be required in an additional study.

In terms of the research strategies adopted, other methods of data collection again would have yielded different results. An ethnographic study of the preliminary design team would have provided data on knowledge interactions between the team, but not across the team boundaries and with the other specialist domains. Also not all design problems are manufacturing-related and this may not have proved to be a beneficial use of time. As previously discussed in 8.2.2, a more rigorous data collection method for research objective 2 would have strengthened the study.

8.3 Limitations of the Study

It is recognised that a major limitation with this study is that it took place within one organisation. This creates difficulties in externally generalising the results. The organisation was selected because it exhibited certain characteristics which made it a suitable subject for the research area. These were:-

- The nature of the product as an assembly of complex mechanical components.
- The nature of the design process. For successful control of the product design both within the organisation and in the tiered supply network, a staged gate review process is used to control the maturity of the design. This segregates the process into a series of stages which approximately conform to the conceptual, embodiment (preliminary) and detail stages of design.
- The size of the organisation, the number of people involved in the product design and problems with geographical co-location.
- The combination of engineering processes required during the design process and the trade-off which is required as a consequence of all these factors.

Arguably, the results of this research could therefore be applied to other organisations exhibiting similar characteristics, although this would need further study.

However, this organisation limitation can also be construed as a benefit. It enabled a very detailed examination of knowledge sharing issues to be undertaken between different domains. The knowledge relating to actual engineering components could be examined in depth. In total, 38 people from the organisation took part in the research at some stage. The qualitative methods of data collection yielded a rich analysis and examination of the issues involved. Such findings were the need for the process maturity and the identification of the different 'thought worlds'. These results would not have been identified in a broader study involving less people in more organisations. Carrying out the research in this way identified research areas relevant and unique to this sector which could be explored further. By limiting the context of the research, the research design could encompass both inductive and hypothesis testing elements. Broadening the context would have resulted in the focus of the enquiry changing to one of these elements.

8.4 Comments on the Methodology Developed

The purpose of the methodology was to create a vehicle for testing the requirements of the hypothesis proposed from research objectives 1 and 2. However, in doing this the methodology also became a prototype practical tool for sharing knowledge within the industrial environment. Certainly, it was presented as such to the key stakeholders and evaluators. Therefore a discussion on the success of the methodology must be an evaluation from both of these perspectives.

8.4.1 The methodology as a means of testing the hypothesis

To be perceived as a successful test vehicle, the methodology needed to be a credible embodiment of the hypothesis requirements as discussed in section 6.3. The knowledge requirements were defined by the process, material, geometric and other characteristics. The intention of these characteristics was to ensure the assessment of process feasibility, capability and cost. The addition of influencing and differentiating characteristics were designed as a measure of process feasibility.

The identification and capture of knowledge requirements was enabled by a series of workshops attended by domain specialists key to the knowledge sharing. This use of workshops and knowledge recording enabled both tacit and explicit knowledge to be used. Thus, the requirements were certainly catered for in the design. The question therefore is how well did these work in practice to successfully evaluate the methodology?

Capturing Requirements

The requirements to be specified in the methodology related to the method of manufacture, capability and maturity, i.e. the feasibility of the process in being able to create the component configuration specified. Although cost was also an initial requirement this was deemed out of scope because this would involve an additional investigation into the nature of costing during the preliminary design stage. Such an investigation requires further work. The requirements to be specified depended on the interpretation and provision of the process, material and geometric characteristics and their categorisation as influencing or differentiating.

Some results were output from the methodology workshop which could be used in its evaluation. However, the results showed that this area required further development. Despite briefings, there was some ambiguity in the definition of the characteristics and consequently this impaired the knowledge requirements supplied. It is not clear whether the difficulty in capturing the requirements was due to the nature of the knowledge itself, or that the requirements had inbuilt uncertainties which made it difficult to define. More development work is required in this area.

Process Maturity

This was carried out by the Process Maturity Audit during the Select process, the first process in the methodology. During the evaluation sessions, the components were deliberately selected so that two methods of manufacture – one in development and one mature – could be compared. This appeared to work out as intended. The exercise was intended as a first initial assessment often based on intuitive attitudes towards the process and therefore it required experienced specialists' input. This worked quite well in practice although it could constrain use of the methodology as a practical application (see next section). In terms of the knowledge that was captured, one would have expected the more mature process to have been easier to quantify, although this did not necessarily seem to be the case. This may have been due to the knowledge capture activities within the methodology.

Use of Tacit and Explicit Knowledge

From observations, the evaluation workshops proved to be an excellent forum for exchanging knowledge about the component and its methods of manufacture. Much anecdotal knowledge was included, out of scope of the methodology requirements, the nature of which was recorded during the second evaluation workshop. Although not strictly relevant to the purpose of the methodology, such additional knowledge could be perceived as adding useful background and context to the knowledge. Hence, the workshops were successful in meeting the criteria for tacit knowledge sharing and this ability was appreciated as being valuable by the participants in the evaluation survey ratings. However, they were not so sure of the value of this knowledge transfer activity as an effective use of time. Perhaps conversational exchanges are not recognised as being part of the project work breakdown structure. Alternatively, it could be seen as an appraisal of the actual knowledge collected during the respective evaluation sessions.

Due to the difficulties in quantifying knowledge in the time constraints of the workshop, it is questioned whether this was the most appropriate forum for capturing numerically codified explicit knowledge (or 'structured knowledge' as it was termed in this study). Perhaps the workshop should be limited to brainstorming the required characteristics and their rationale. The quantification could then take place as a follow-up activity, where the knowledge could be referenced or computed, with a further workshop afterwards to view the results.

A major disadvantage of the evaluation is that preliminary design domain specialists were unavailable to take part in the workshop sessions. This would have been useful in examining the tacit knowledge exchanges. Such exchanges may have further assisted in creating a shared context between preliminary design and manufacturing specialists which may have better specified the level of knowledge required. Further work is required to verify this.

8.4.2 The methodology as a practical application

This section discusses how appropriate the developed methodology is as a practical tool which can be used to capture and share manufacturing knowledge for preliminary design in an industrial setting. It is therefore important to consider whether this discussion can be limited to the organisation featured in the research, or to include the possibility of the methodology's use in other organisations. Here, there is a benefit in that the methodology does not feature a prescriptive design process, therefore it has a degree of flexibility which lends itself to being tailored to fit different organisations and design processes.

There are two ways to approach this:-

1. The methodology could be adapted to fit a specific organisation and design process (for the purposes of this thesis, the sponsoring organisation).
or

2. The methodology remains independent and can be incorporated into different organisations and types of design processes.

Each approach has advantages and disadvantages and will be discussed in turn.

Adopting the methodology to fit a specific organisation

In this case, the methodology would be integrated with the organisational design process. The method of recording and recalling the knowledge captured would need to be integrated with existing organisational systems.

The advantages of this approach would be:-

1. The knowledge-sharing activity between preliminary design and manufacturing would become an integral part of the design process of the engine project and therefore be included by default. This should pave the way for a more rigorous risk assessment of new manufacturing processes during early preliminary design.

2. In order to introduce a new business process or system it is essential that the user community has ‘buy-in’, that is, actively participates in its creation and use. Integration with the existing business process would by default result in greater buy-in.

3. By linking to existing systems there would be less duplication of data.

The major disadvantage with this approach is that there may be a mismatch between the methodology and existing processes and systems. A major part of the methodology implementation would entail the closing of this gap. In doing so, the implementation team would need to ensure that this did not dilute the intentions and benefits in implementing the methodology.

Implementing the methodology as an integrated part of the design process and systems would require the following major project phases:-

1. Further development of the methodology. This would require a further user requirements capture stage to ensure that the methodology would work in a way sympathetic with the users’ task. This requirements capture would be from a practical users’ perspective rather than the research perspective adopted for this thesis. During this stage it is essential to set clear boundaries for the scope of the implementation in order to have a timely roll-out.

2. Analysis of the methodology and current design process. This would be undertaken to understand how and where the methodology fits with the current design process and how to best tailor it to fit with the process. At this stage it is essential to ensure that the methodology intentions and benefits stand up.

3. Analysis of current design support systems. This would be a similar activity to 2 but undertaken from a systems perspective. The outcome of this stage would specify whether the system to support the methodology would be an enhancement of an existing system or an additional tool. Investigations would need to examine how best to present, record and re-use the relevant knowledge. System support and maintenance would also be an important factor (see point 6).

The first three stages can be partitioned into individual segments of work, however it would be beneficial to run them concurrently as the results of all will impact on each other. Several iterations of the requirements may be required.

4. Methodology and system implementation. This stage features the usual expected stages of ICT project implementation: the configuration (or creation) of the software system (depending on the solution selected) and business processes, documentation of these, testing, user acceptance testing and user training.

5. Roll-out. A decision would need to be made early in the project to determine the scope of the eventual roll-out. It is suggested that this is carried out on a small pilot initially before commitment to a larger-scale deployment. The scope of the initial roll-out could be confined to a specific subset of components for an engine project.

6. Ongoing support and maintenance. This was an issue which was highlighted during the methodology evaluation sessions, especially by the preliminary design team. It is vital that the knowledge in the system is kept updated and current in order for it to be used successfully for risk assessments during preliminary design. Ensuring that this is carried out and making this process transparent to the users is necessary to establish trust and therefore maximise buy-in into the knowledge recorded. The methodology includes the Review process, out of scope of this study, which would need to be created and implemented as part of this. The requirements for methodology / system support and maintenance - what needs to be done, when and by whom - would initially need to be explored and specified during activity 3 above. This would ensure that the requirements are manageable within the scope of day-to-day work.

Using the methodology independently of the organisational processes

With this second approach, the methodology would continue to function in the format seen in its development and evaluation in this study, that is, as a set of processes sitting alongside but independently of the main preliminary design process. The supporting ICT system would also be independent of other organisational tools.

The advantages of this approach are:-

1. Implementation and roll-out could take place in a short time frame because the analysis of the methodology and current systems and processes (steps 2 and 3 of the implementation for the first approach) are no longer required.
2. The methodology would be more flexible and adaptable to future changes to the design process.

3. Methodology and system maintenance and support would be easier. More integration between systems and processes can result in potentially more and complex problems, i.e. being affected by a patch upgrade in COTS software.

The disadvantages are:-

1. Because the methodology is not closely integrated with the design process, there is the risk that it will be seen as an optional activity. This could reduce user buy-in which, as discussed previously, is essential to the success of any process or system.

2. The knowledge recorded may be duplicated in other systems, especially structured knowledge. This is problematic for the entire design process, is a waste of user effort and may reduce trust (and hence use) in the system.

The implementation of the methodology as an independent set of processes and supporting ICT system would require the following project stages:-

1. Further work on the methodology. This would be further development to ensure that the methodology will meet requirements from a user's perspective rather than a research perspective. This would probably involve a re-appraisal of the 'Select' and 'Create' processes, further work on the most appropriate 'Use' process and the creation of the 'Review' process. The outcome of this stage would ideally be a clearly defined and 'ready to use' set of methodology processes.

2. Specification of the methodology ICT support system. This could be either a system written in-house tailored to the specific methodology requirements, such as a database linked to intranet web pages. Alternatively a COTS solution may be the best option. The system requirements would need to be scoped and specified, including not only functionality but also support and maintenance requirements.

3. Implementation.
4. Roll-out
5. Ongoing support and maintenance

These follow the same format and hence the same issues as steps 4, 5 and 6 respectively for the integrated methodology.

8.5 Recommendations for Improving the Knowledge Identification, Acquisition and Sharing

Outside the boundaries of the methodology, the findings of the study have further implications for the management of manufacturing knowledge during preliminary design, particularly concerning the ways in which knowledge identification, acquisition and sharing can be improved. The recommendations are:-

1. In terms of knowledge identification, it is important to identify the characteristics of a product or process where there is an element of immaturity in the knowledge associated with the product or manufacturing process. This demonstrates an element of risk in the product which will need to be managed and mitigated.

2. In terms of knowledge acquisition, cross-functional approaches have been verified as being critical. The intended use of the knowledge to be acquired will vary according to the domain specialism. It is important for those involved in such an activity to be aware of this, as the knowledge to be supplied may not necessarily be that which would be perceived as being most relevant. Clarifying the knowledge required and the rationale for that knowledge in such activities would be a simple but effective step.

3. In terms of knowledge sharing, other knowledge transfer activities should be implemented to improve the links between preliminary design and the functions which are responsible for manufacturing process developments. This could increase the awareness of how these processes can impact on component configurations and increase the options explored at the beginning of a new engine project. This would be an important activity to operationalise recommendation 1. Such knowledge transfer activities should embrace both the tacit and explicit elements of knowledge and be a formal method within the process, similar to the formal social network of the IPTs used in later stages of the design process.

4. The configuration impact attributed to a new manufacturing process remains constant as a manufacturing process matures, although the extent of that impact will become more quantifiable. The assessment of the geometric characteristics in the methodology defines that size and shape. This would be a useful early exercise to identify manufacturing features - the attributes from which process capability could be measured as the process matures. As the process matures, these features could become standardised.

8.6 Contributions to Knowledge

1. An investigation into engineering knowledge management has been carried out using an interpretive, flexible research design and phenomenological enquiry techniques. This type of research design has not conventionally been applied to this subject area. The use of this methodology complements and (to a certain extent) triangulates research in this area which has used more 'conventional' techniques. However, it has also emphasised the social knowledge sharing aspects and requirements needed in an industrial setting.

2. A hypothesis has been developed which defines the requirements for innovative manufacturing knowledge during the preliminary stage of design for complex mechanical components. This hypothesis supports and

consolidates previous research themes of tacit and explicit knowledge, codification and maturity of knowledge.

3. A practical methodology has been created from the hypothesis which demonstrates a combined tacit and explicit approach for knowledge management for innovative manufacturing knowledge during the preliminary design stage of complex mechanical components.

8.7 Conclusions of the Study

1. The preliminary design stage in the case studied for this research is concerned with an initial feasibility assessment before the more detailed DFM – type activities commence in the next stage. The reason for this it to mitigate risks which will become more costly to correct at a later stage.

2. The content for manufacturing knowledge at preliminary design level is similar to that of the more detailed stages in that it encompasses method of manufacture, process capability and cost. However, an additional key requirement at preliminary stage is knowledge about the maturity of the manufacturing processes available because this is the main risk to be mitigated. The manufacturing knowledge is abstracted in that a geometrical impact is sufficient to explain the manufacturing effect for this stage of the design process. The reasons for this geometrical impact become relevant for later design stages.

2. The main driver for manufacturing knowledge in preliminary design is the impact of the manufacturing process on the component configuration, hence the feasibility of achieving this configuration is key. This can be directly related to the component function and material selected.

3. The impact on component configuration as described in point 2 can be advantageous as it leads to the possibility of exploring new component configurations which can better satisfy or even improve on functional requirements. However, the risks must be appreciated, especially in situations where the process is new to production and hence the associated knowledge is uncertain.

4. Hence, methods of collating and sharing knowledge which has some degree of uncertainty is key in sharing manufacturing knowledge between the design and manufacturing specialist domains during preliminary design, Expressing knowledge in both tacit and explicit ways with varying degrees of codification are instrumental in this.

5. The design process puts artificial barriers in place of the flow of knowledge due to the required product (geometric) maturity at each process stage. Additionally, differing perceptions of knowledge requirements create different 'thought worlds' for design and manufacturing specialists. These impede knowledge flow, creating 'knowledge gaps' which impact on the effectiveness of the design process. This may

well be why manufacturing problems are encountered despite the introduction of Concurrent Engineering techniques.

6. Therefore knowledge management techniques should concentrate on cross-domain knowledge sharing methods for improvements in preliminary design. The findings from the study are the requirements for such a technique.

7. A pilot methodology was developed incorporating these requirements and tested. This demonstrated some effectiveness, especially regarding the process maturity and knowledge types used.

8.8 Future Work

8.8.1 Future work concerning the methodology

Further development and definition of the methodology is required, particularly in the definition of the characteristics and the means by which this can be successfully achieved. However, it is recognised that this requires the more effective definition of something which is, by nature, difficult to define.

A case which was not tested during the evaluation session was the tacit knowledge sharing between preliminary designers and manufacturing engineers. This could take place during the workshop systems and is recommended as further work to better defined the manufacturing knowledge content required.

The above would assist in preparing the methodology to be applied practically in an industrial setting. However, other aspects also need to be examined for business readiness. These are:-

- The integration of the methodology with existing business process.
- Selection and implementation of suitable ICT systems to support the methodology.

8.8.2 Future research work

1. The hypothesis created as part of this research can be investigated and tested in other situations to test whether it applies and the limits at which it applies. Suitable candidates could include other companies in the aerospace sector or other industry sectors which also produce complex mechanical engineering systems (such as energy). The hypothesis could also be tested across component complexity to investigate the limits to which it can be used.

2. A main conclusion of this research was the need to use different knowledge types and strategies to deal with the uncertainty of knowledge generated. Research should be carried out to examine whether this is also the case for other types of knowledge required during the preliminary design stage. An area of current research and

therefore a good candidate for consideration for this specific case would be service considerations.

3. Research could also be carried out to further investigate whether the 'knowledge maturity' aspect is unique to preliminary design or whether it does actually also exist for later stages of the design process. This may have not been previously investigated due to simplification of the product and process for later stages of design. Ideally, this research would take place in a sector responsible for complex mechanical engineering systems.

4. The hypothesis could be extended in the future to investigate how changes at component level (due to the development of manufacturing processes) affect change propagation within the sub system of a complex mechanical component.

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Appendices

Appendix A: Example of coding analysis spreadsheet from interviews

(Excerpts from the full analysis)

Linking examples of manufacturing impacts and knowledge types

1	I spoke to one of the designers...But I don't think there's any intranet site or anything you could go to, to find out what all the (manufacturing) minimums are'	Refers to manufacturing impact 1 (m/f mins on shrouded HP turbine blade)
1	You basically have your blade off design and your pressure design and manufacturing minimums and whole engine modelling loads and you just pick the thickest out of all of those. We may have a Plum Folder on that. All our design rules are in there	Refers to impact 2 (m/f mins casing)
2	The experts there are the manufacturing engineers and they have run the analysis and the tests on test pieces to say essentially what materials they've tried to bond together. So that's where we get the information about what materials we can match together and the quality of that bonded joint.	Refers to impact 6 (inertia bonding of HP compressor drum)
5	Some of them have got standard elbows on. I'm looking back to what's been done before and I think some of these bend radii are using the routing practices defined in the JDS. DRAs as well'	Link to structured knowledge and standardisation

Knowledge preferences

1	...you'd almost have to have everyone's detailed design for the whole engine, for us to work on. There're ten or eleven designers in Prelim design for the whole engine, and I don't know how many hundreds of detail designers there are out there.	Preference for unstructured knowledge use
2	That's where the expert knowledge is, there's literature on the subject, it can be useful but it tends to be a lot simpler to ask the people who know, go straight to the horse's mouth.	Refers to m/f impact 6. Preference for unstructured knowledge use when semi-structured is available.
2	It's generally a matter of who do you ask? Who do I ask about this subject? And within half an hour you'll get a good understanding of what the issues are. Generally that's the way we work. It's not a knowledge-based system in that respect.	Preference for unstructured knowledge use?
3	Use of website: 'to get a bit of background really, then I'd go and talk to one of the experts.'	Use of semi-structured for general knowledge, backed up by unstructured for detailed information
3	We would do, if a new material was known to be available, we would get that from the materials group because they have a website and they say what they're doing. We have meetings with them, well, I don't personally, but in the department every individual	Use of unstructured knowledge to back up semi-structured
4	I'm perhaps well positioned to say that I would love a recipe book of what to do and what to watch out for, you know, which hasn't always been there and it's hard to find out.'	Need for structured knowledge
4	And you need the experience and need to have gone through the hurt to know that	Need of own unstructured knowledge? (experience)

Appendix B: Development of Initial Code

(Developed after first set of interviews)

The interviews were transcribed and a data driven code developed. The unit of analysis was each interview; the unit of coding was each critical incident. In addition to the critical incident, salient points about knowledge, knowledge sources and knowledge uses were also analysed.

A manifest-content analysis code was developed which identified two main themes: manufacturing impact and knowledge type. Each them was further subdivided, to create a total of six themes:-

Manufacturing Impact – Quantified
Manufacturing Impact – Capability
Manufacturing Impact – Standardisation
Knowledge type – structured
Knowledge type – semi-structured
Knowledge type - unstructured

The full list of coding and associated features is as follows:-

Manufacturing Impact - Quantified

Definition: This code occurs when the current manufacturing process constrains the size of the component to certain parameters. These parameters are expressed numerically. The constraints imposed by these parameters must be considered in a trade-off with other design requirements (i.e. sizing limitations from lifing) with the 'worst case' sizing being the final design case.
How to know when the theme occurs: Reference to maximum or minimum allowed dimensions due to manufacturing. These dimensions are applicable to current manufacturing processes. These dimensional constraints can be seen across most components in the general arrangement. They will be considered routinely as part of the design process. The interviewee may or may not be aware of the manufacturing process with constrains the dimensions.
Qualification: Any constraint named must at least be described as 'due to manufacturing'. A description of the manufacturing process is a good qualifier, but is not essential.
Positive examples:-
Minimum allowed wall thickness of a component due to the casting process.
Maximum forging size allowed for bought-in component of finished material.
Manufacturing maximums and minimums.
Negative examples:-
Minimum allowed component thickness.
Maximum casing size. (reasons for maximum / minimum not given).

Manufacturing Impact - Capability

Definition: occurs when the results of a design improvement exercise are compromised by the immaturity of the manufacturing capability to produce the product. This can also include assembly or joining techniques.
How to know when the theme occurs: interviewee will discuss a number of options for a design change. At least one of the options will not be feasible due to the capable manufacturing process being unavailable.
Qualification: The theme will be qualified if the manufacturing process is a development of existing manufacturing technology, or the application of existing manufacturing technology to a new situation, i.e. it is deemed in some way to be theoretically feasible. *Disqualification*: The theme will be disqualified if there is no consideration of the feasibility of the manufacturing process.
Positive examples of this theme:-
Change of a bolted joint to an inertia bonded joint.
Change of the profile or shape of a component to improve its function, with considerations of how the manufacturing should take place.
Negative example:-
The proposed manufacturing process is not feasible.

Manufacturing Impact - Standardisation

Definition: this code occurs when component or component features are selected from a predetermined list of standard sizes. These standard sizes are fixed by the manufacturing process, or the supplier (and their manufacturing process?).
How to know when this theme occurs: the interviewee will indicate that the component or feature is standardised. The interviewee may or may not know the details of the manufacturing process or reasons for the standardisation. One characteristic of this impact is that there very rarely seem to be many issues relating to it, as if the standardisation is accepted. Often the part will be bought-in and the standardisation will be defined by the supplier.
Qualification: The theme will be qualified if there is discussion of standardisation.
Disqualification: It will be disqualified if some parameterisation or customisation is allowed to the component.
Positive examples:-
'Standard range of pipes and fittings'.
'Use of a previous part as standard'.
Negative examples:-
'We'll select an existing part from a previous assembly and modify the sizings'.

Knowledge Type – Structured

Definition: Examples of manufacturing engineering knowledge which can be expressed numerically, by algorithms or numerical rules. Information is generated and used during the design process. This information is repeatable across projects. Documented in the form of parameters, dimensions, spreadsheet calculations or algorithms in expert systems. Can also be expressed graphically. Knowledge is said

to be 'abstracted' – it is possible (although not always preferable) to apply it without fully appreciating the circumstances in which it was created.
How to know when it occurs: Design requirements and/or information is expressed numerically. The format is stand-alone and can be repeatedly be used as a tool. Details of the manufacturing process which forms the knowledge may or may not be included.
Qualification: The theme is qualified if the knowledge can definitely be quantified and is document based.
Disqualification: It is disqualified if there is a degree of qualitative knowledge and/or if the knowledge is not documented.
Positive examples:-
Manufacturing minimums and maximums.
Graphically-represented parameterised feature.
Negative examples:-
Reference material (such as material properties) referred to, but not generated as part of the design process.

Knowledge type - semi-structured

Definition: Examples of manufacturing engineering knowledge which can be expressed quantitatively or qualitatively. Referenced during the design process – supports, but is not integral to the design process. Need to reference will depend on the situation, the context and the designer's own experience. Documented in text documents. Knowledge is said to be 'embedded' – the designer needs to be able to browse and understand the context of the knowledge in order to be able to use it. Often the knowledge referenced is from outside the department.
How to know when it occurs: Examples of numerical or descriptive information as seen in text documents.
Qualification: The theme is qualified if the knowledge is not documented as an abstracted rule or algorithm or graphical image.
Disqualification: The theme is disqualified if there is no documented evidence of the knowledge.
Positive examples:-
Material properties
Descriptions of manufacturing processes.
Negative examples:-
Conversational discussions.

Knowledge type – unstructured

Definition: Examples of manufacturing engineering knowledge which can be expressed quantitatively or qualitatively. Referenced during the design process – supports, but is not integral to the design process. Need to reference will depend on the situation, the context and the designer's own experience. Knowledge is said to be 'embedded' – the designer needs to be able to browse and understand the context of the knowledge in order to be able to use it. Often the knowledge referenced is from outside the department. Knowledge is not recorded and is communicated via social networks, hence the expert being questioned can supply some context. Theme can

occur inside and outside the department, and be formal and informal communication methods.
How to know when the theme occurs: the knowledge is communicated socially.
Qualification: The qualification of this theme is the manner in which it is communicated, i.e. socially. The content of semi-structured and unstructured knowledge is the same, it is the vehicle of communication which differs.
Positive examples:-
Discussions with people, group meetings.

Appendix C: The MCRL Process

The MCRL (Manufacturing Capability Readiness Level) is a scheme developed by the Manufacturing Technology department at Rolls-Royce. It is a development of the Technology Readiness Levels (TRLs) devised by NASA applied to the development and productionisation of new manufacturing technology. It is currently being launched on new engine projects within the company.

Programme Phase	MCRL	State of Development
Phase 1: Technology assessment and proving	1	Process concept proposed with scientific foundation
	2	Acceptability and validity of concept described and vetted, or demonstrated
	3	Experimental proof of concept completed
	4	Process validated in laboratory using representative development equipment
Phase 2: Pre-production	5	Basic capability demonstrated using production equipment
	6	Process optimized for capability and rate using production equipment
Phase 3: Production implementation	7	Capability and rate confirmed via economic run lengths on production parts
	8	Fully production capable process qualified on full range of parts over significant run lengths
	9	Fully production capable process qualified on full range of parts over extended period (all business case metrics achieved)

Definition of the Rolls-Royce MCRL Process (reproduced with permission from Rolls-Royce plc)

The full MCRL process involves a number of stage gate reviews and documented supporting evidence. The aim of the Select process maturity audit is to carry out a very quick intuitive assessment based on experience. As the MCRL process is new and being gradually introduced, there are a number of legacy manufacturing processes which have not been assessed. The process maturity audit represents a very quick way of assessing the process maturity in these cases.

The definition 'in development' i.e. those cases where an empirical expression of impact is desired correlates to MCRL levels 5 upwards. A mature process correlates to MCRL levels 8 and 9. A truly standardized component actually does not apply to the MCRLs, it is actually beyond level 9, therefore is referred to as '9+'. A process needs to reach stage 9 as a pre-requisite to being standardized. Levels 1-4 inclusive of the MCRL scale are not in scope of the process maturity audit because in order to be considered for a new engine project then at least some evidence of pre-production success is required.

Appendix D: Methodology Screenshots

Figure D.1: Methodology introduction slide

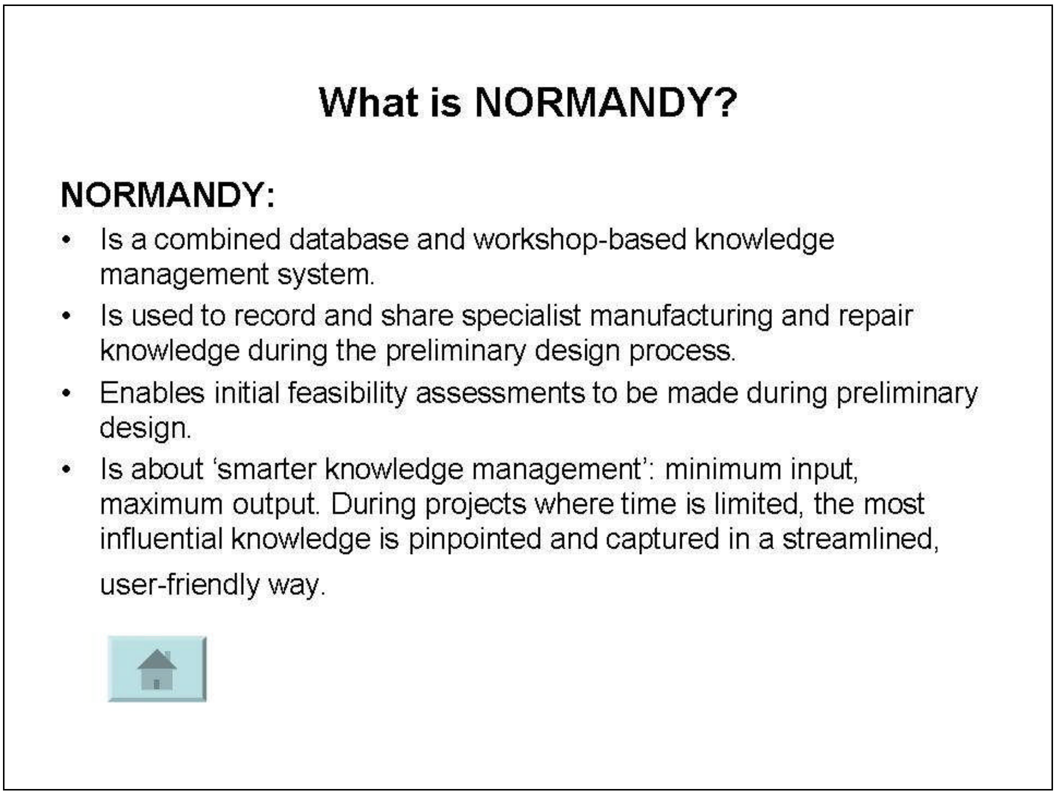

Figure D.2: Methodology introduction slide

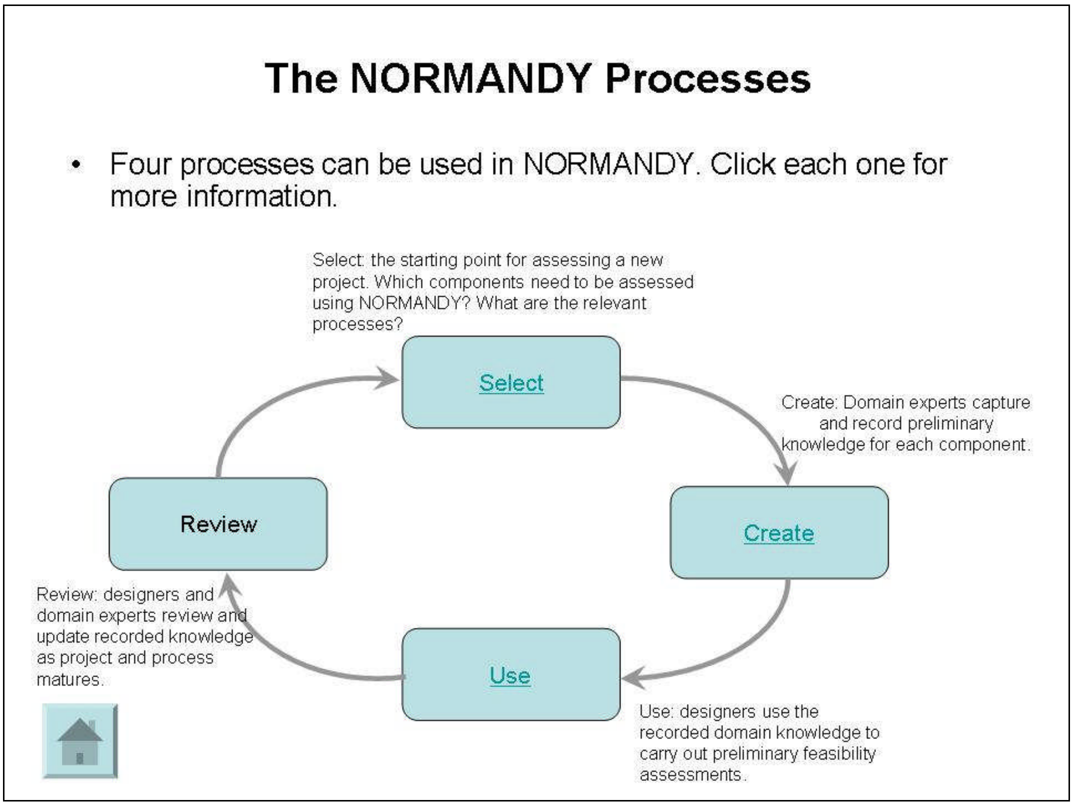

Figure D.3: Methodology processes slide

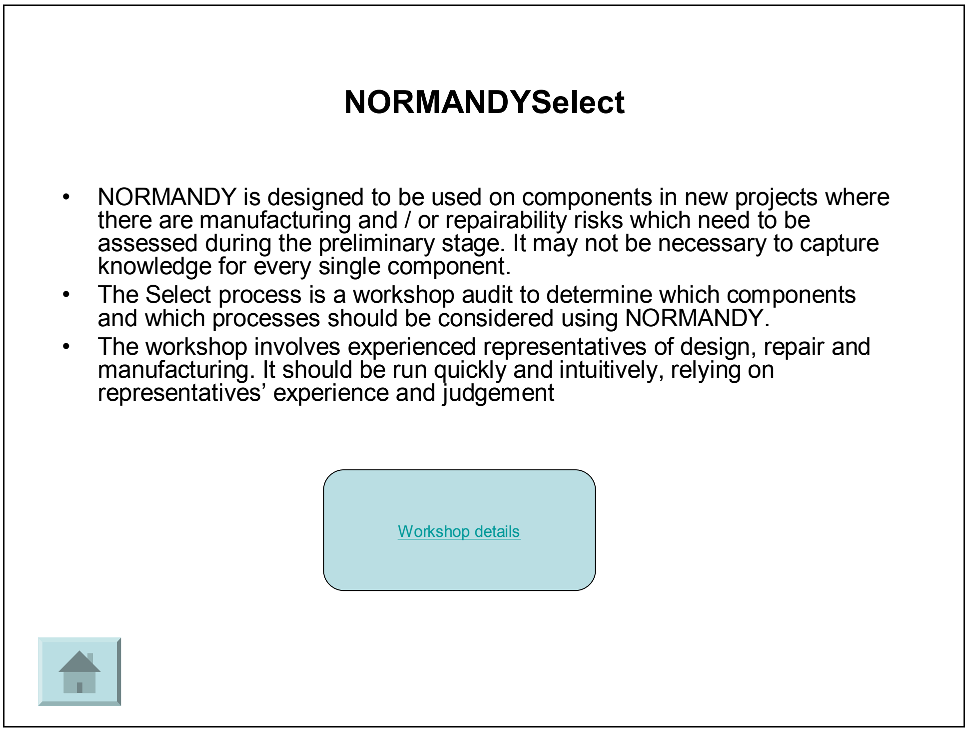

Figure D.4: Select process introductory slide

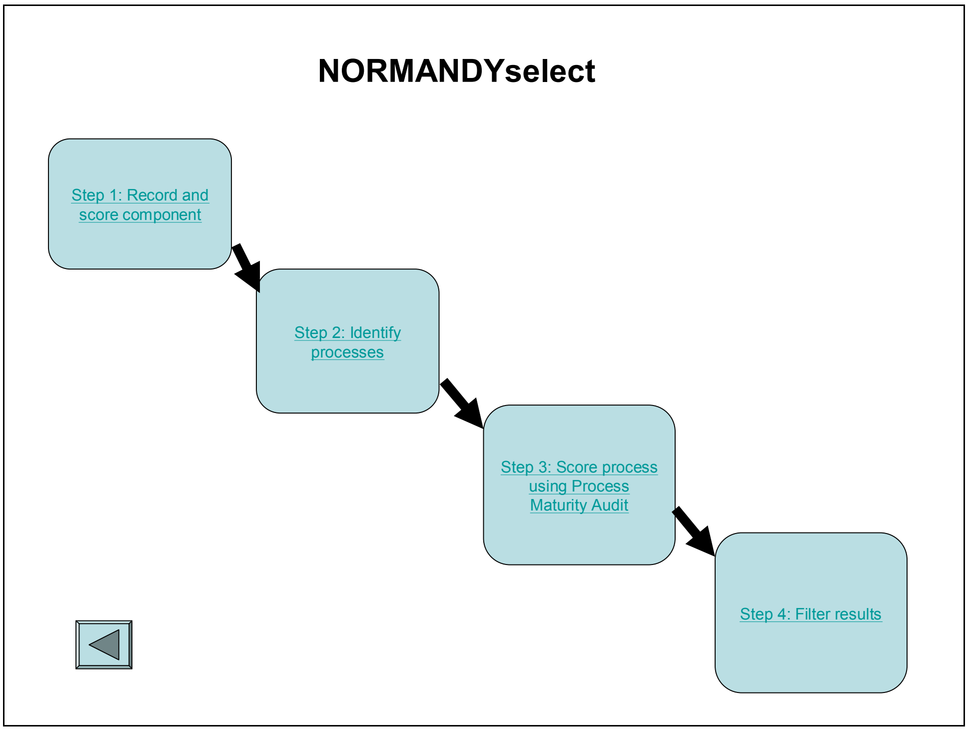

Figure D.5: Select process steps

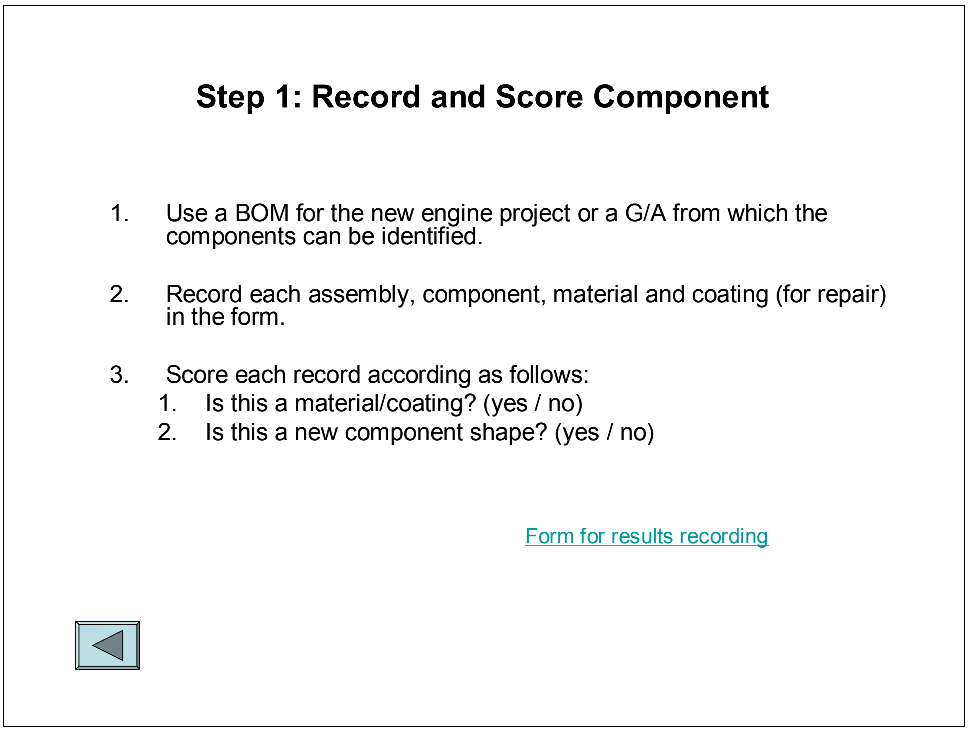

Figure D.6: Select process slide

Step 2: Identify processes

Identify the following for each component and assembly listed on the form:-

1. Methods of manufacture.
2. Methods of assembly / joining.
3. Methods of repair.
4. Methods of inspection.
5. Treatment processes.

Add these to the form.

Form for results recording

Figure D.7: Select process slide

Step 3: Score Process Using the Process Maturity Audit

- Each process recorded in step 2 needs to be rated as being in development, mature or standardised.
- Read through the statements in the process maturity audit and decide which description applies to each process. Update the form accordingly.

Form for results recording
Process Maturity Audit

Figure D.8: Select process slide

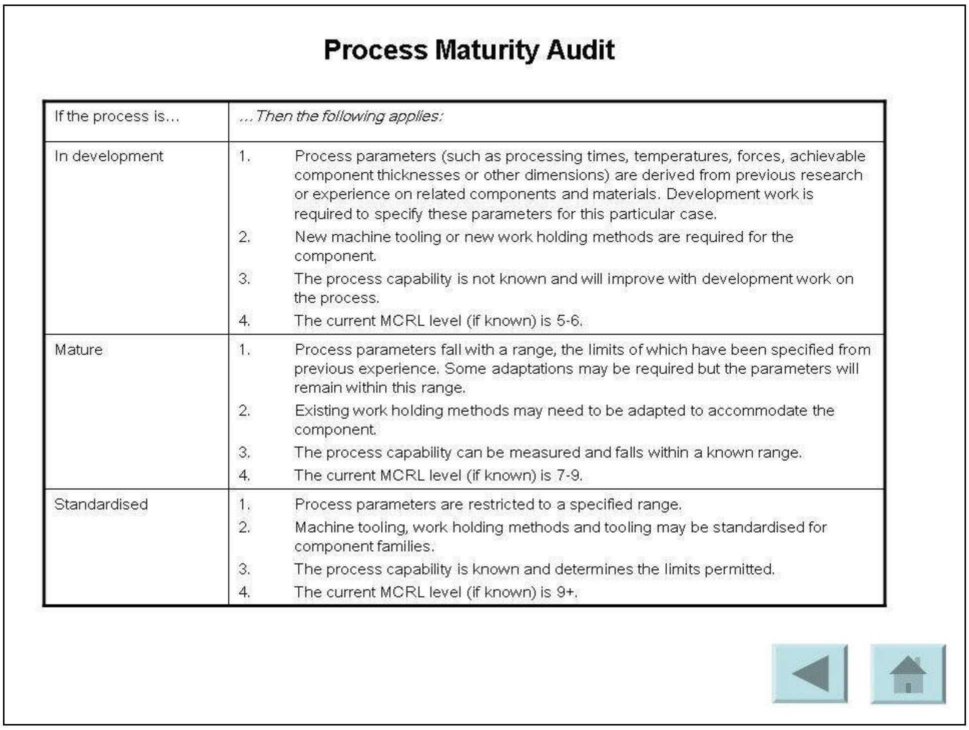

Figure D.9: Select process slide (process maturity audit)

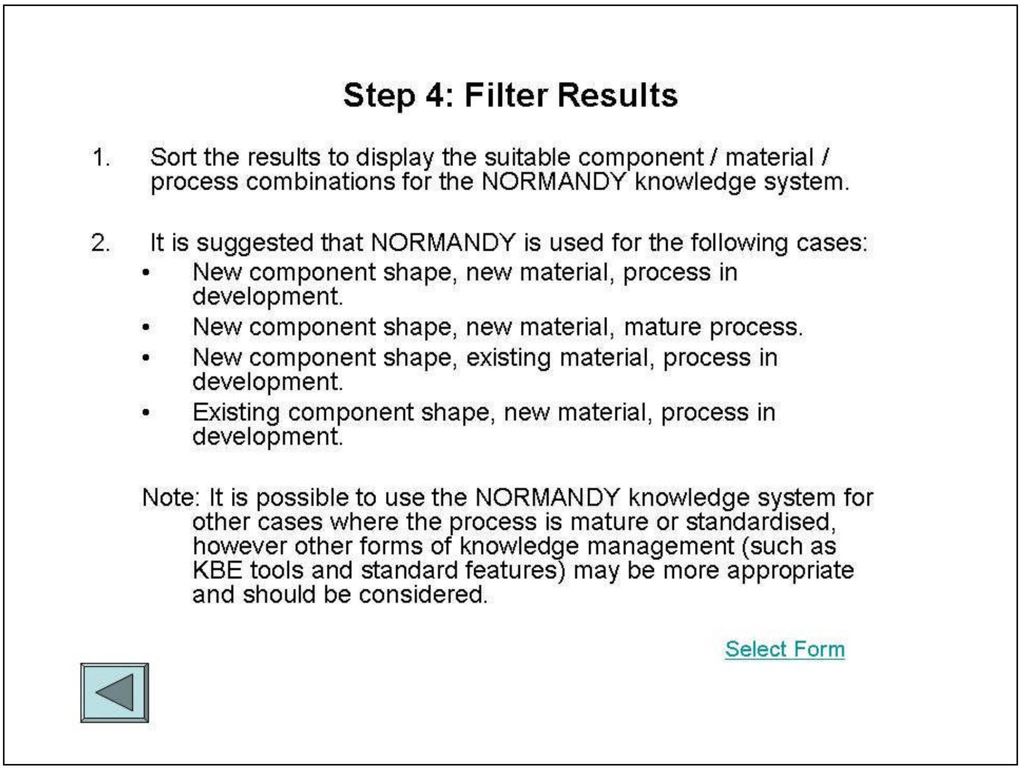

Figure D.10: Select process slide

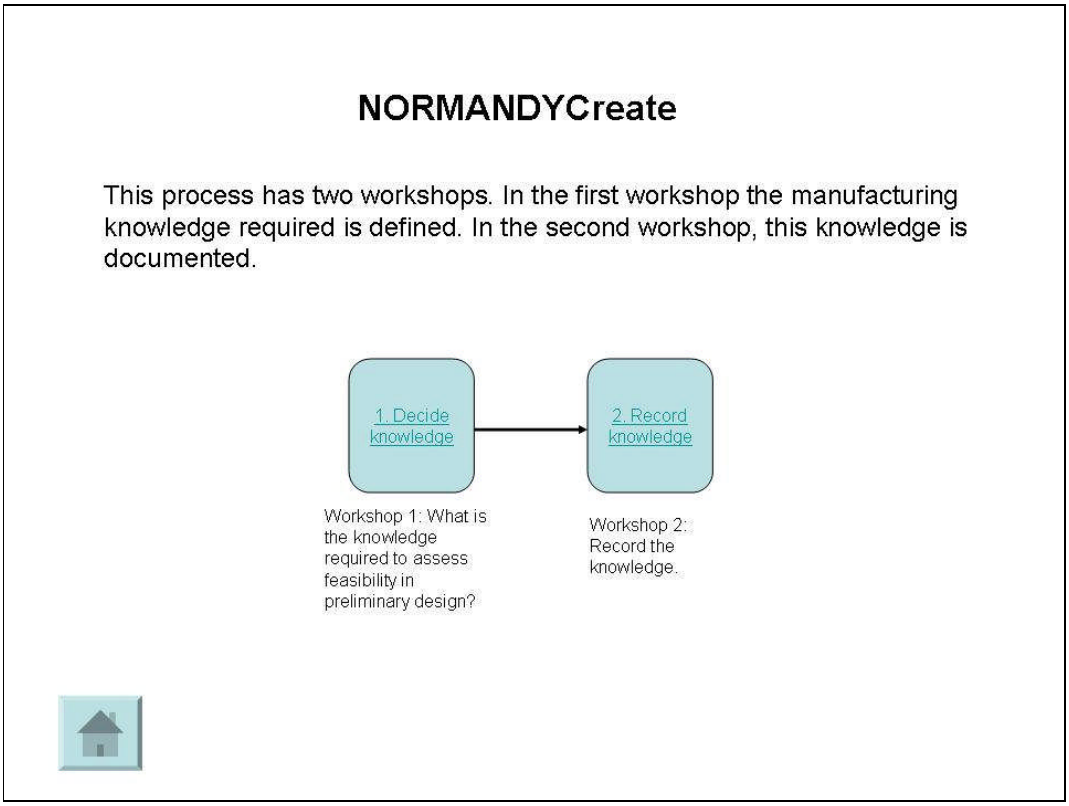

Figure D.11: Create process slide

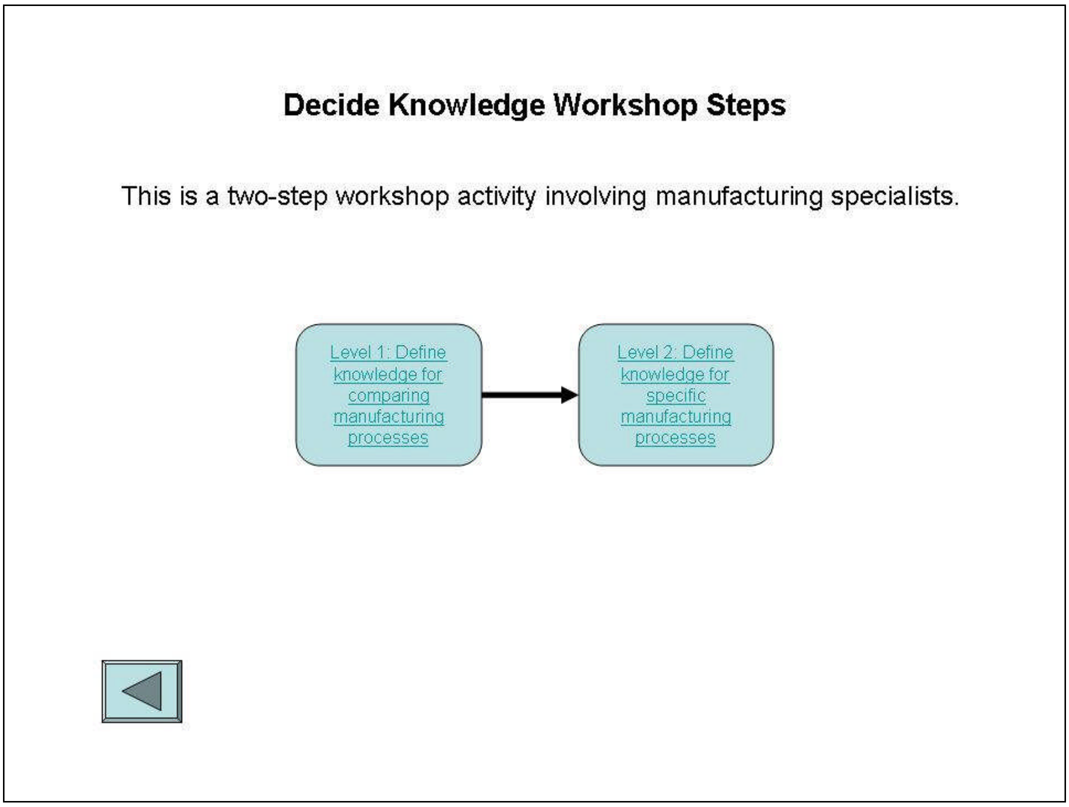

Figure D.12: Create process slide

Define knowledge for comparing manufacturing processes - 1

In this activity you identify the manufacturing knowledge required to compare the different methods of manufacture listed during the Select process. The results are all recorded in Level 1 of the Create form.

1. Enter:
   - –The engine project;
   - –Component description;
   - –Material;
   - –Available methods of manufacture;
   - –Manufacturing process specialist contact details.

Create form

Figure D.13: Create process slide

Define knowledge for comparing manufacturing processes - 2

2. Identify the characteristics which can be used to differentiate between methods of manufacture. These can be:

Material characteristics

These are aspects of the material properties of the component which constrain the method of manufacture available for selection.

Process characteristics

These are aspects of the manufacturing process which constrain its ability to manufacture the component.

Geometric characteristics

These are aspects of the component geometry which are constrained by the selected method of manufacture. These can be dimensions, overall shape and size or surface finish requirements.

Other characteristics

There may be other miscellaneous constraints on the manufacturing process selection which don't fall into the above three categories but still need to be considered.

Figure D.14: Create process slide

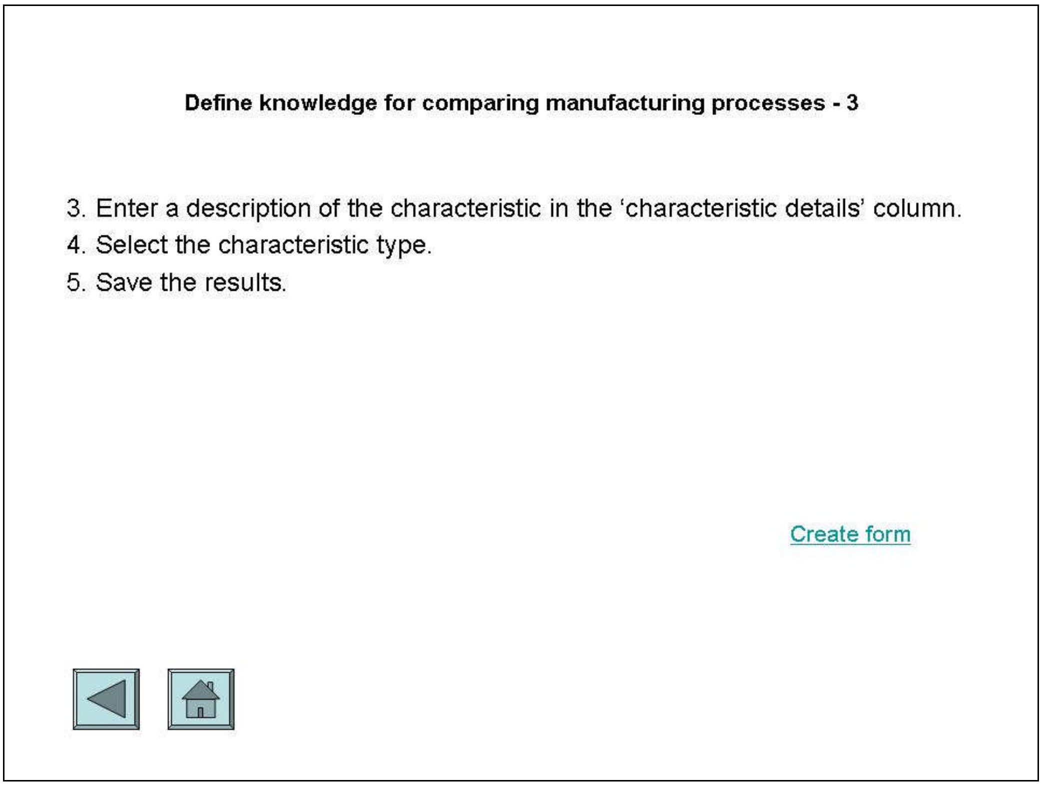

Figure D.15: Create process slide

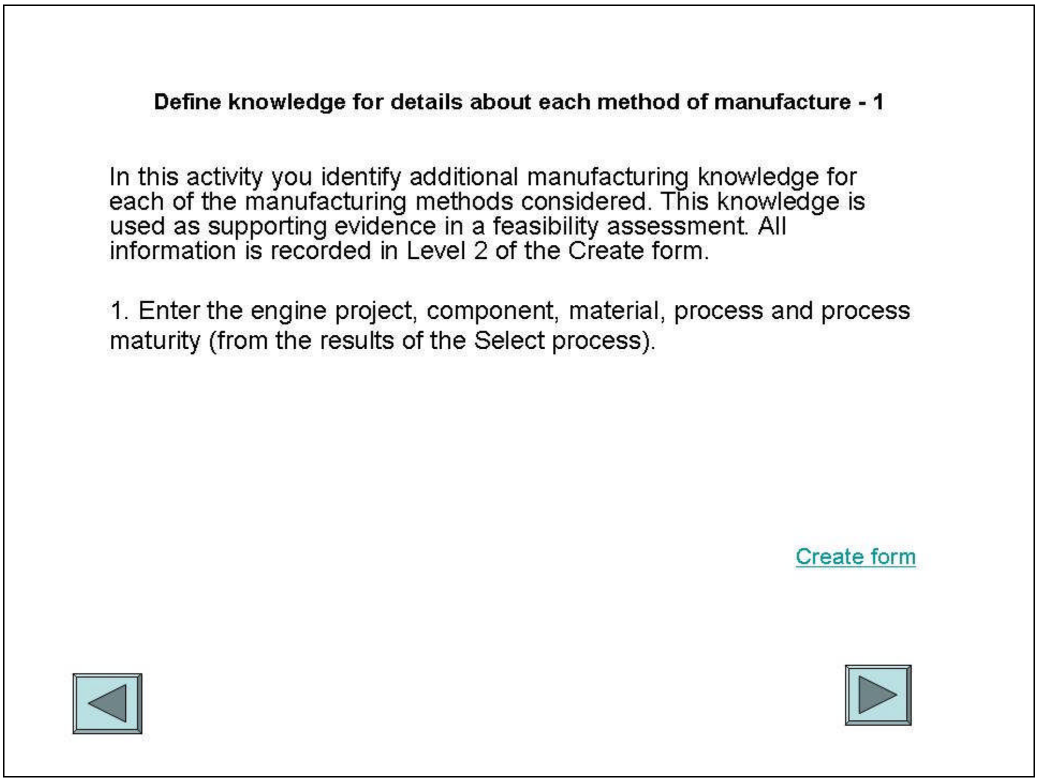

Figure D.16: Create process slide

Define knowledge for details about each method of manufacture - 2

2. Identify the characteristics which are required for process-specific manufacturing knowledge. These can be:

Geometric characteristics

These are aspects of the component geometry which are constrained by machine tools, tooling or other equipment. These can be dimensions, overall shape and size or surface finish requirements.

Material characteristics

These are aspects of the material properties of the component which constrain the method of manufacture available for selection.

Process characteristics

These are aspects of the manufacturing process which constrain its ability to manufacture the component. The following specific process characteristics can constrain and apply at this level:-

The capacity and availability of required production facilities.

The estimated lead time for component production.

The estimated unit cost of the component using the method of manufacture.

The process capability.

The capability readiness (MCRL level) of the process / component.

Other characteristics

Other miscellaneous constraints on the manufacturing process selection may need to be considered.

Figure D.17: Create process slide

Define knowledge for details about each method of manufacture - 3

3. Enter a description of the characteristic in the 'characteristic details' column.

4. Select the characteristics type.

5. Save the results.

Create form

Figure D.18: Create process slide

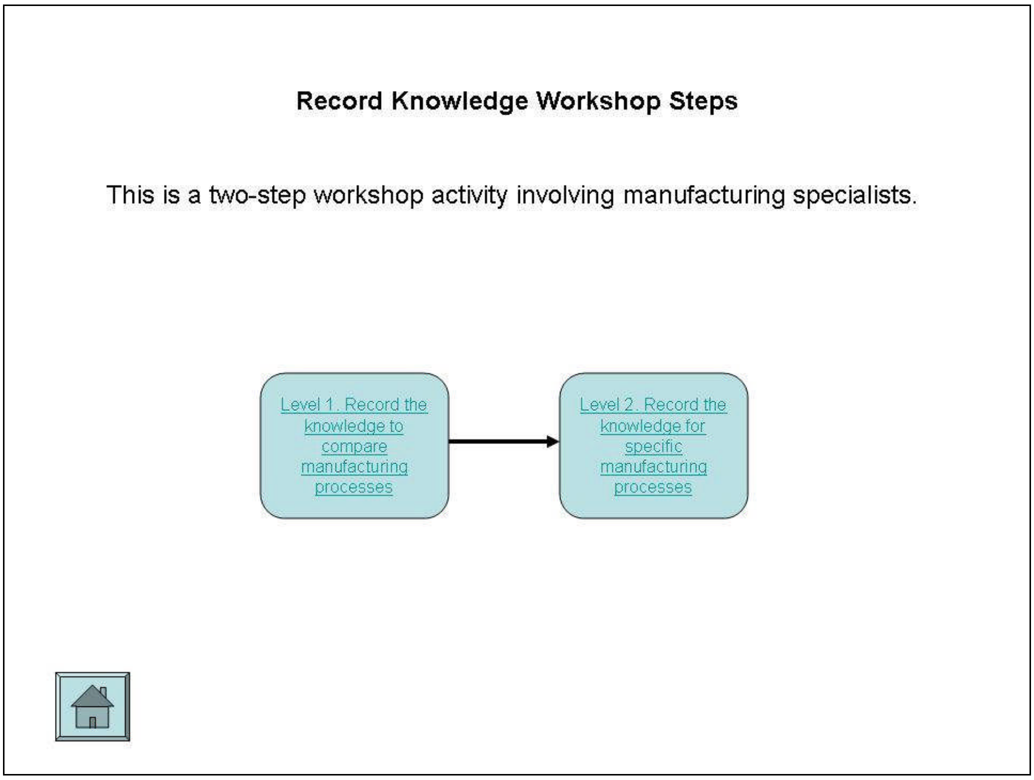

Figure D.19: Create process slide

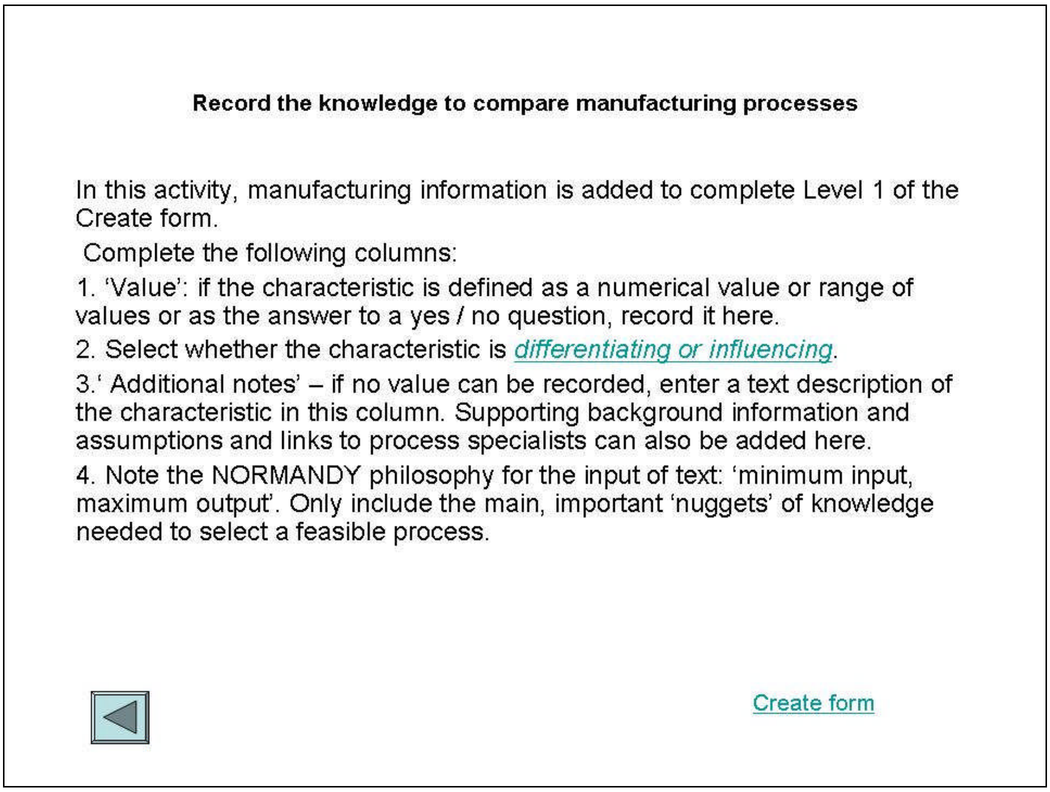

Figure D.20: Create process slide

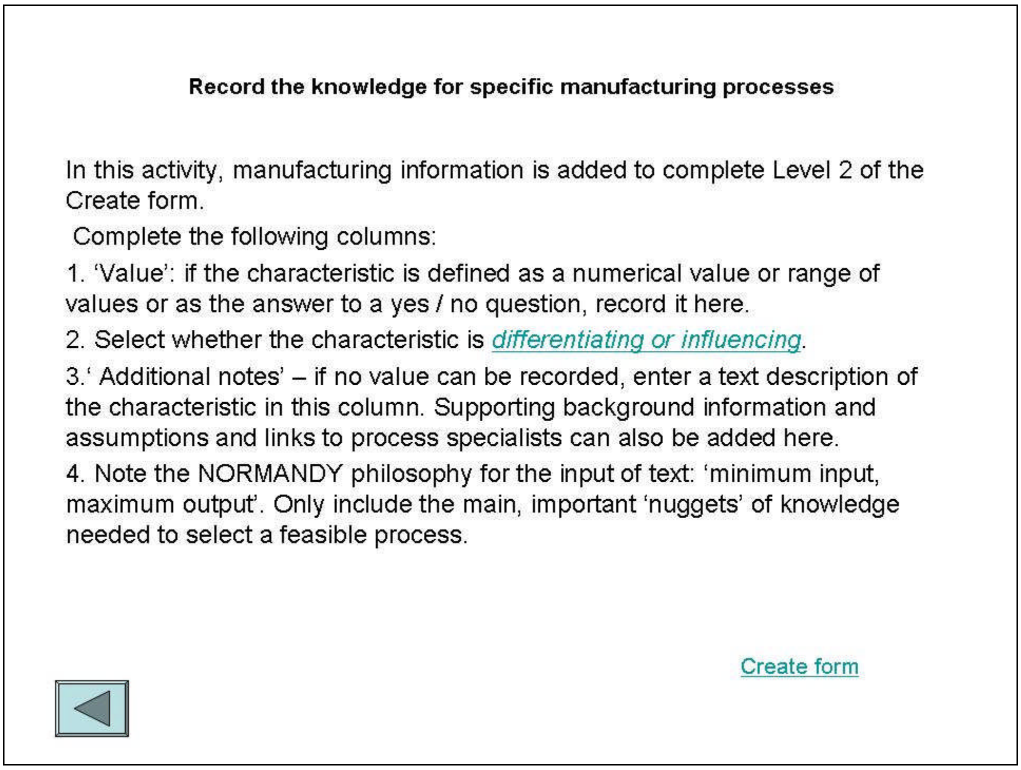

Figure D.21: Create process slide

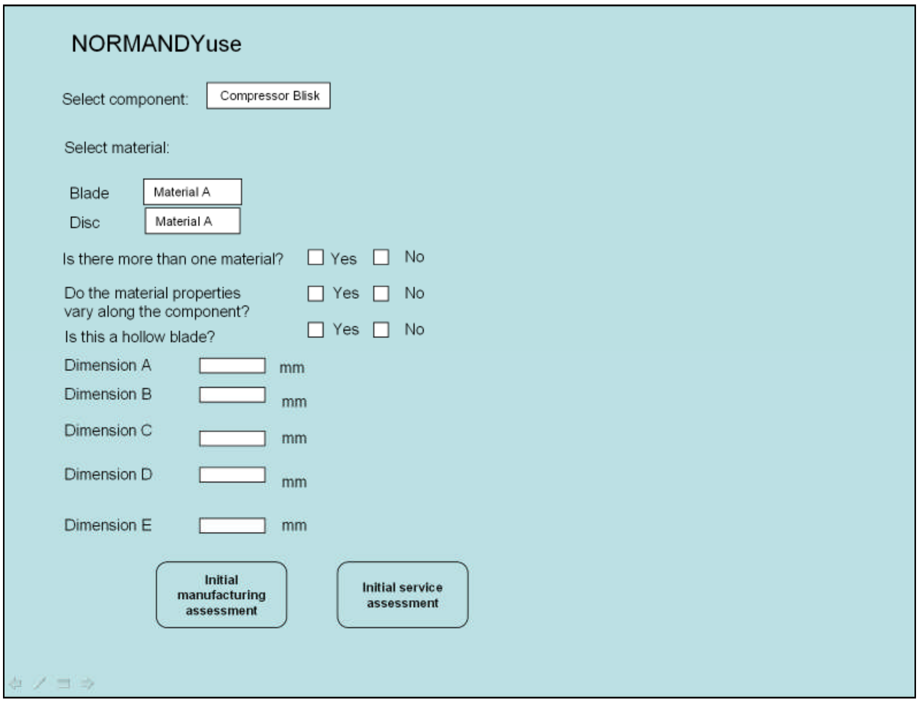

Figure D.22: example of 'use' form

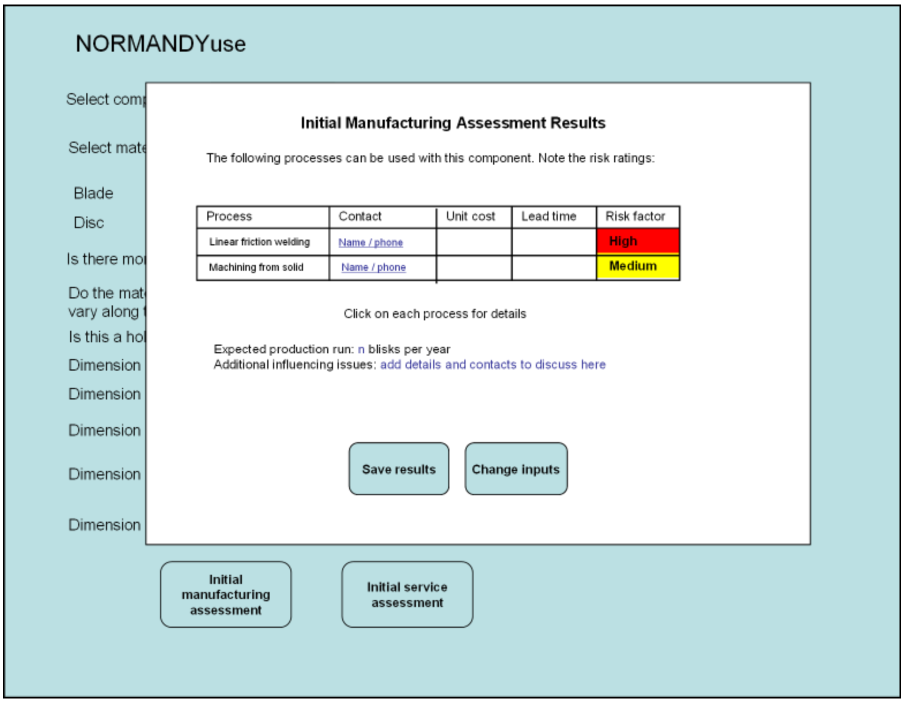

Figure D.23: example of 'use' form

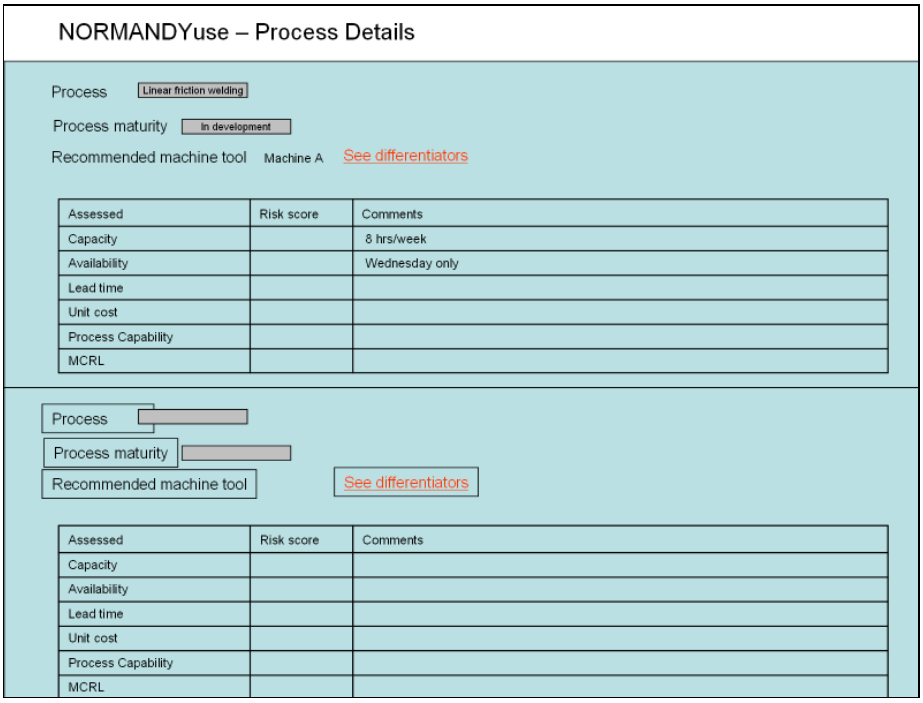

Figure D.24: example of 'use' form

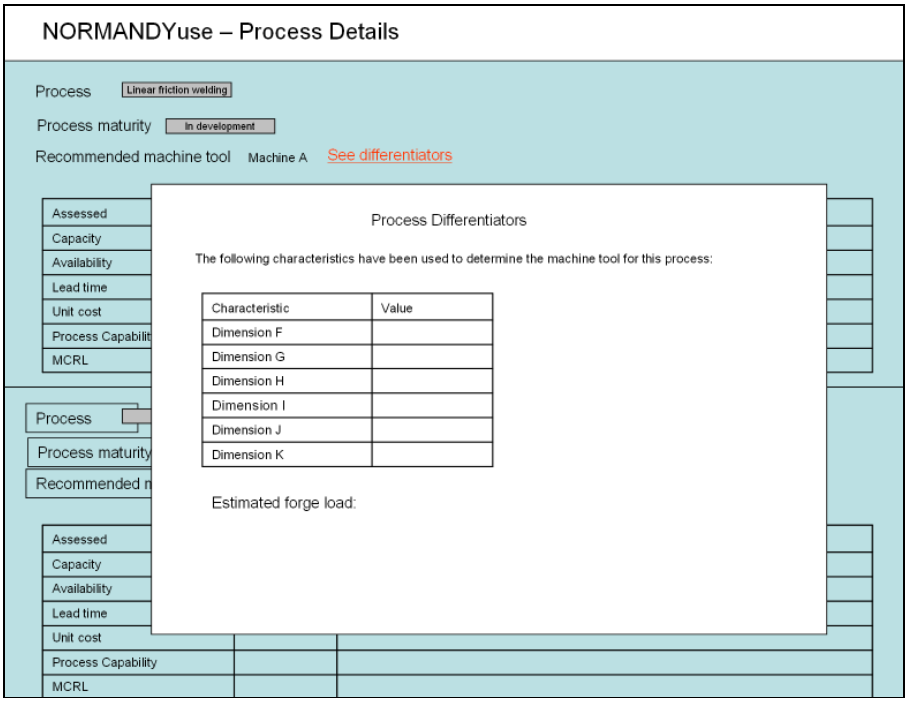

Figure D.25: example of 'use' form

Appendix E: Evaluation Surveys

Manufacturing Evaluation Form

(Used for manufacturing specialists in the Select and Create workshops)

Section A: Introductory questions

A1. How would you describe your role in preliminary design?
(Divides respondents into design and manufacturing domains for survey analysis)

Manufacturing process specialist	☐
Designer	☐
Other (please state)	_____

A2. Do you carry out stage 1 preliminary design tasks as part of your job role?
(Inquires whether respondent is familiar with stage 1 NPI process)

Yes	☐
No	☐
Don't know	☐

A3. Do you know what manufacturing knowledge is required to assess process feasibility during stage 1 preliminary design?
(Inquires whether respondent is aware of stage 1 manufacturing process) requirements)

Yes.	☐
No	☐
Don't know	☐

Section B: Workshop 1 – the Select process

Read each statement about the Process Maturity Audit. Circle the answer which best matches your opinion.

B1. I understood the statements in the audit.
(The PMA was clearly written and unambiguous)

1	2	3	4	5	6
Strongly disagree					Strongly agree

B2. The process maturity was assessed quickly.
(The PMA is designed to give a quick, intuitive assessment of process capability. This question is designed to see if the participants agree).

1	2	3	4	5	6
Strongly disagree					Strongly agree

Section C: Workshop 2 - The Create Process (Decide Knowledge)

Read each statement and circle the number which best matches your opinion.

C1. I was able to understand what was required from the workshop.
(The workshop guidance notes should be clearly written and unambiguous. This question tests this).

1	2	3	4	5	6
Strongly disagree					Strongly agree

C2. Identifying the characteristics was easy to work through.
(Again, tests how clear and ambiguous the required task is).

1	2	3	4	5	6
Strongly disagree					Strongly agree

C3. Identifying the characteristics was quick to work through.
(Tests if the workshop can be run quickly as designed).

1	2	3	4	5	6
Strongly disagree					Strongly agree

C5. Listing the characteristics was more effective than general discussions
(The methodology is designed as a systematic process to gather knowledge more effectively and comprehensively than a discussion. Question added to see if participants agree if this is the case).

1	2	3	4	5	6
Strongly disagree					Strongly agree

Section D: Workshop 3 – The Create Process (Record the Knowledge)

Read each statement and circle the number which best matches your opinion.

D1. I could identify the knowledge required.
(Inquires whether the participant was able to identify the required knowledge content by identifying examples of the characteristics).

1	2	3	4	5	6
Strongly disagree					Strongly agree

C4. It was useful to distinguish between differentiating and influencing characteristics.
(Inquires if there was any use in differentiating between constraints which would drive a process decision, and constraints that would be supporting evidence in a

business case. Note, this question was originally in section C for the first two workshops. Although moved to section D, it has retained its original number to compare directly with results from the other two workshops).

1	2	3	4	5	6
Strongly disagree					Strongly agree

D2. Recording manufacturing knowledge as numerical information was...

1	2	3	4	5	6
Not at all useful					Very useful
1	2	3	4	5	6
Too time-consuming					An effective use of time

D3. Recording manufacturing knowledge as additional comments was…

1	2	3	4	5	6
Not at all useful					Very useful
1	2	3	4	5	6
Too time-consuming					An effective use of time

D4. Being able to be able to discuss the manufacturing knowledge requirements in a workshop setting was...

1	2	3	4	5	6
Not at all useful					Very useful
1	2	3	4	5	6
Too time-consuming					An effective use of time

(Questions D2, D3 and D4 are designed to test the usefulness of the different knowledge types in identifying and compiling the knowledge).

Section E: Comments about the workshop and outcomes

E1. The content of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design.

(Assesses whether the participants are of the opinion that the knowledge content identified through the methodology is suitable for an initial feasibility assessment).

1	2	3	4	5	6
Strongly disagree					Strongly agree

E2. The level of detail of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design.
(Assesses whether than manufacturing knowledge has been supplied at an appropriate level for stage 1 initial assessment).

1	2	3	4	5	6
Strongly disagree					Strongly agree

E3. Compared to the manufacturing knowledge I would use in my job role, the knowledge recorded is…
(Again, an assessment of the level of knowledge required. A 'less detailed' scoring indicates that the level of knowledge requires does need to be filtered to a more abstract level for preliminary design, if the answer to E2 has been affirmative).

1	2	3	4	5	6
Much less detailed					Much more detailed

E4. It was useful to be able to combine recording numerical and text knowledge in the same form.
(An assessment of the usefulness of using 'explicit' knowledge types – structured and semi-structured – in the methodology).

1	2	3	4	5	6
Strongly disagree					Strongly agree

E5. It was useful to be able to combine recording knowledge (as text and numerics) and workshop discussions.
(An assessment of the usefulness of using both tacit and explicit forms of knowledge in the methodology, as structured, semi-structured and unstructured knowledge).

1	2	3	4	5	6
Strongly disagree					Strongly agree

E6. What was the most useful part of the workshop for you? Why?
E7. What was the least useful part of the workshop for you? Why?
E8. What changes would you recommend to the methodology? Why?
E9. Would you be interested in using any aspect of this methodology in your job role?
(Some initial enquiries into the suitability of the methodology, or some of its elements in NPI).

Yes	☐
No	☐
Don't know	☐

Why?

E10. Look back at your original answer to question A3. Having completed this workshop, has your opinion changed?

Yes.	☐
No	☐
Don’t know	☐

Why?

E11. Any further comments?

Thank you for your participation.

Designers' Evaluation Form

(Used for preliminary design specialists appraising the knowledge which would be presented as part of the Use process)

Section A: Introductory questions

A1. Do you know what manufacturing knowledge is required to assess process feasibility during stage 1 preliminary design?

(Same question as for the manufacturing specialists, aimed to assess if there is some involvement in the manufacturing process assessment at present).

Yes.	☐
No	☐
Don't know	☐

Section B: Comments about the form

(These questions are largely identical to those in section C of the Manufacturing Evaluation forms. The motivation for asking them is the same).

B1. The content of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design.

1	2	3	4	5	6
Strongly disagree					Strongly agree

B2. The level of detail of the manufacturing knowledge specified is sufficient to allow an initial process feasibility assessment to be carried out during stage 1 preliminary design.

1	2	3	4	5	6
Strongly disagree					Strongly agree

B3. Compared to the manufacturing knowledge I would use in my job role, the knowledge recorded is…

(Ideally, a score around 3-4 would be expected here. The manufacturing knowledge should be 'about the same'.)

1	2	3	4	5	6
Much less detailed					Much more detailed

B4. It is useful to have numerical and text knowledge and contact details for specialists combined in the same form.

(Tests the effectiveness of the knowledge being presented in a way that uses all the different knowledge types).

1	2	3	4	5	6
Strongly disagree					Strongly agree

B5. The form distinguishes between knowledge which constrains manufacturing process selection and knowledge which is background for a business case.

1	2	3	4	5	6
Strongly disagree					Strongly agree

B6. It is useful to distinguish between knowledge which constrains manufacturing process selection and additional knowledge for a business case.

1	2	3	4	5	6
Strongly disagree					Strongly agree

Section D: General Comments about the form

D1. What was the most useful part of the form for you? Why?
D2. What was the least useful part of the form for you? Why?
D3. What changes would you recommend to the form? Why?
D4. Would you be interested in using any aspect of this form in your job role?

Yes ☐
No ☐
Don't know ☐

Why?

D5. Look back at your original answer to question A1. Having reviewed the form, has your answer changed?

Yes. ☐
No ☐
Don't know ☐

Why?

D6. Any further comments?

Thank you for your participation.