CRANFIELD UNIVERSITY

JESSE IAN BAILEY

CUTTING TOOL DESIGN KNOWLEDGE CAPTURE & REUSE

SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE

EngD THESIS

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CRANFIELD UNIVERSITY

DEPARTMENT OF ENTERPRISE INTEGRATION

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JESSE IAN BAILEY

Cutting Tool Design Knowledge Capture & Reuse

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ABSTRACT

Cutting tools play an important part in today's manufacturing industry. There is an ever-increasing pressure on the cutting tool design industry to produce better quality products in response to the needs of the automotive and aerospace industries. Add to this the increasing complexity of the machined product requiring the use of non-standard cutting tools. The consideration of this area of cutting tool design is in recognition of the importance of the information and knowledge requirements at the beginning and during the design process. It has been noticed that in the cutting tool industry that the knowledge provision lacks structure and organisation. Understanding the knowledge requirements of the designers would provide substantial benefits to the design process. Thus, this research explores the role and extent of special purpose cutting tool design knowledge.

Literature review shows there is a lack of research examining the knowledge of designers within special purpose cutting tool design. The design of a special purpose-cutting tool is a knowledge intensive task. This thesis presents a novel methodology for Knowledge Elicitation called Knowledge = Expert – Novice (KEN). KEN is a methodology requiring active participation in the design task. It is demonstrated that KEN is suitable for the capture of cutting tool design knowledge. KEN is used to examine the nature and extent of special purpose cutting tool design. It is observed that KEN provides a structured approach to the Knowledge Elicitation from an expert. An in-depth investigation of the preliminary design stage has revealed the knowledge required by special purpose cutting tool designers.

This thesis presents an ontology-based framework for cutting tool design knowledge representation following a functional, structural and behavioural methodology. The knowledge is represented by base-functions, ways of achievement and design considerations organised into functional hierarchies. The ontology is validated by domain experts rating the terms within the ontology and by cases. It is observed that the ontology is a complete representation of the cutting tool design knowledge. A viewpoint of design reuse is modelled to include a set of descriptor terms and captured domain knowledge. The viewpoint is mapped onto the ontology to provide a set of generic terms. The reuse viewpoint is then implemented onto Case-Based Reasoning software to search for past designs. The reuse viewpoint is then validated using a number of case studies and user trials. It is demonstrated that the reuse viewpoint is effective for the extraction of terms from design documentation, searching for and recalling past designs.

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LIST OF ACRONYMS

AI	Artificial Intelligence
CAD	Computer Aided Design
CAPP	Computer Aided Process Planning
CBR	Case Based Reasoning
DIN	Deutsches Institut für Normung e.V.
EngD	Engineering Doctorate
EPSRC	Engineering & Physical Sciences Research Council
GT	Generic Tasks
KBS	Knowledge Based Systems
KEN	Knowledge = Expert – Novice
ISO	International Standards Organisation
MBA	Masters of Business Administration
MRR	Metal Removal Rate
NC	Numerical Control
OEM	Original Equipment Manufacturer
PSM	Problem Solving Method
PVD	Physical Vapour Disposition
SAE	Society for American Engineers
SEM	Shared Expertise Model
WWW	World Wide Web

CHAPTER ONE

Introduction

1.0 OVERVIEW

Within the manufacturing industry, cutting tools play a vital role. The automotive and aerospace industries depend on the services provided by the cutting tool industry. The industry however is mature with a few big players competing for the right to supply customers their tools. The nature of the industry is changing, and the customers require the tooling industry to provide greater services than ever before. In the past the cutting tool organisation would have just provided a cutting tool as and when required by the customer. However, the new service criterion is to provide tooling solutions to the customer where the cutting tool organisation must provide total tooling on-site.

The value and importance associated with the machining process at these customer's sites has increased the level of quality of the design of cutting tools to fulfil these machining needs. The needs are for a wide variety of tools to machine a range of diverse and complex components for which it is very rare indeed that a standard cutting tool can do the job that is required. The requirement is for a special or one-off set of cutting tools. This has led to the increase in complexity of the cutting tool and hence the design of these tools.

The process of the design of special purpose cutting tools requires the matching of the customer's requirements interpreted by the designer, to produce a design. In many instances the designer will search for a past design that will match some of the criteria set out in the customer's specifications. The variety of insert/toolholder/component material selection adds to the complexity and hence the task of cutting tool design is knowledge intensive. It takes up to five years to become proficient at cutting tool design and 20 years or more to be called an expert.

This study concentrates on the knowledge requirements of cutting tool designers throughout the design process. The consideration of this area of cutting tool design is in recognition of the importance of the information requirements at the beginning and during the design process. It has been noticed in the cutting tool industry that the information provision lacks structure and organisation. Understanding the information requirements of the designers would provide substantial benefits to the design process.

This thesis describes the exploration of the design processes within the cutting tool design industry by participation in a typical industry design process. This established the knowledge requirements of designers during the design task. It provides a structured approach to the capture and representation of this knowledge. This research is carried out through an Engineering Doctorate (EngD) programme.

In the next section an overview to the EngD programme is discussed. The background to the collaborating company will be discussed in section 1.2 giving an indication to its strategic position in the cutting tool industry and the reasons for its participation in this research. Section 1.3 discusses both theoretical and practical cutting tool design identifying why it is a knowledge intensive domain. Finally, in section 1.4 a research problem and research aim is given. This is followed by the research approach in the form of a thesis structure. Thus, the aim of this chapter is to introduce the context of the research and subsequently this thesis.

1.1 THE ENGINEERING DOCTORATE PROGRAMME

Despite the high standard of research in British universities, there has been concern expressed about the relevance to industry of narrowly defined problems, in particular the role of conventional doctorates within engineering disciplines (Reynolds, 1997; Argument, 2000). In response to this the Engineering & Physical Sciences Research Councils (EPSRC) (formerly Science and Engineering Research Council or SERC) were required to investigate and develop a programme that would solve the issues raised with the conventional doctorate within the UK. The result was the establishing of the Engineering Doctorate (EngD) Programme, which was piloted in 1992 with three British universities. In 1993, two further universities (including Cranfield University) joined the programme. In 2001/2, due to the further success of the programme the number of universities that offer the EngD totals 15 universities (EPSRC, 2002).

During the programme, new knowledge and skills obtained from an intensive programme of taught coursework are applied to one or more doctoral level industrial research projects (EPSRC, 2002). The EngD research and training aims to (EPSRC, 2002):

- Provide the Research Engineer (RE) with the experience of rigorous, leading edge research in a business context;
- Develop competencies which equip research engineers for a range of roles in industry;
- Provide a mechanism and framework for high quality collaboration between academic groups and a range of companies;
- Contribute to the body of knowledge on a particular technical discipline, industrial sector or multidisciplinary theme.

The EngD is of four-year duration to allow the research engineer to establish a relationship with the industrial partner (Argument, 2000). This ensures that whilst the work is relevant to the sponsoring organisation, the research engineer is also able to develop generic principles, which are useful to similar organisations (Reynolds, 1997). Also, in keeping the central tenet of the EngD programme, the research engineer develops a broad appreciation for the relevance of their work.

Each institution is allowed to design its own course structure within the remits of the EPSRC guidelines. Typically there are two camps on the style of course that is provided by the universities participating in the programme. Research Engineers may provide a single, traditional thesis, or a series of documents covering their research projects. This latter portfolio approach includes a single summary bringing together the overall contribution to knowledge and innovation demonstrated by the Research Engineer (Anon., 2002b). This portfolio approach also includes examined management and technical lecture courses, together with presentations to improve communication skills (Anon., 2002a). The approach taken at Cranfield University is to have the Research Engineer submit a single thesis, a taught and examined Executive Masters of Business Administration (MBA) taught course and a range of taught technical courses.

The next section describes the background and current state of the collaborating organisation.

1.2 THE COLLABORATING ORGANISATION

This section discusses the background and current position of the collaborating organisation strategically in the cutting tool industry. This project was carried out with Widia Valenite UK. Widia Valenite is a multinational company manufacturing and designing metal cutting equipment. The United Kingdom site is a design site specialising in the design of specials for the UK market. Specials are one-offs and tooling sets for particular applications for which standard tooling would not be suitable. Its main customers are in the automotive, aerospace, energy, OEM and other industries. In 1997, sales of special steel products was £2.7million and in the same year sales of special carbide products was £3million; with the automotive industry accounting for 43% of these sales. During the past six months Widia Valenite UK has been bought by Kennametal, however this has not influenced the project as the experts that were used in the research are still at the UK site. The following sections will describe the history of the organisation prior to the takeover.

1.2.1 Valenite

Valenite was founded in 1943 as a small special tool shop serving the automotive industry and its suppliers. It was originally named Modern Corporation and later MODCO, with the first products being custom-made from ground high-speed steel tools followed soon after by special brazed carbide cutting tools. In 1954, the firm added a subsidiary for the manufacture of carbide cutting tips, single point boring bars, simple tool-holders and a standard line of interchangeable tooling. This operation was the basis for today's worldwide organisation known as Valenite. In February 1993 Valenite became a wholly owned subsidiary of Cincinnati Milacron.

1.2.2 Widia

More than 75 years ago a company named Krupp gained the industrial rights to a new hard material known as tungsten carbide, which was to revolutionise the metal cutting industry. Tungsten carbide is a sintered material that is as 'hard-as-diamond' and hence through the German for 'like diamond' – WIe DIAmant, the brand name WIDIA was introduced. The late 1920's saw rapid development for the trademark WIDIA with the development of drawing dies made of the hard material, the first tools to turn cast iron, brazed hard metal tips were born and in 1928 WIDIA tools were used to machine steels. The 1930's saw WIDIA being awarded Grand Prix at world metal cutting expositions. The product range now incorporates the entire spectrum of tools for turning, drilling and milling all materials plus mining tools, knives and saws. Further advancement of materials introduced the use of titanium carbide to enhance cutting performance. WIDIA maintained an 84% market share into the war years.

1.2.3 Influence of Cincinnati Milacron

In 1995 Milacron purchased the German based Widia, which was then a leader in turning, milling and standard tooling and by 1998 it combined the operations of Valenite and Widia under the brand name "Widia Valenite", thus integrating the metal cutting insert tool business with annual worldwide sales of $500million primarily producing carbide cutting tool inserts, insert holders and metal working fluids. While developing, manufacturing, and marketing common products and services worldwide under the new Widia Valenite brand, the existing legal entities of Widia and Valenite remained intact. The new organisation has gained global integration of product design, manufacturing processes, capacity management, and information technology systems. Moving toward common global product design will reduce design, engineering, manufacturing and marketing costs and lower inventory levels. New tooling and cutting fluids developed by the new organisation will be marketed under the Widia Valenite brand. Its global capabilities consist of:

> *Valenite* – North America's leading innovator of metal-cutting technologies for turning, milling, and standard tooling.
> *Widia* – Valenite's European counterpart, an acknowledged leader in turning, milling, and standard tooling products.
> *Valenite's MODCO products* – the world's leading source for special tooling packages used in block and cylinder head manufacturing systems.
> *Widia's Heinlein products* – the world's leading source for special tooling packages used in crankshaft manufacturing systems.

This section has described how the collaborating organisation came to be. In the next section the author examines the strategic issues for the UK cutting tool industry and discusses the challenges that the industry faces over the next few years.

1.2.4 Strategic Issues for the UK Cutting Tool Industry

The cutting tool industry in the UK is highly competitive with four to five large players and several smaller companies fighting for market share. All these companies offer a specialist design service providing special cutting tools for the major industries in the manufacturing sector. Over the last few years the UK manufacturing sector in general has seen a downturn in activity, which proposes a number of issues in the cutting tool industry as this downturn, affects their business also. However, the worldwide growth for cutting tools is set to continue and the UK market shows signs of recovery. The cutting tool industry faces many challenges over the next few years including:

Integrated supply chains – These major customers are looking to completely outsource their tooling needs which require the cutting tool companies to become experts in logistics as a major criterion for the customer selecting a cutting tool manufacturer. This has led to the 'big getting bigger' resulting from major consolidations and cutting tool manufacturers merging to provide these logistics.

How and why will the customer buy from us? – This has resulted from increased globalisation and an increase in the Far East cutting tool market providing far cheaper solutions. E-commerce has had an effect on the industry with many of the big players providing interactive WWW sites that provide an expert system based problem solver to aid the customer to assess what his/her needs are, and then sending this to the design teams to be designed and manufactured.

Improvements in cutting tool technology – Improvements in cutting tool technology progress steadily, and we see improvements in work pieces in terms of types of material being used. Because of this, manufacturers are developing new cutting tools to meet the needs of the end users. The emphasis is primarily on carbide tools, which can operate at a greater speed than the high-speed steel tools including the designing of tools with coolant through-holes. Coatings are being developed to increase tool life, with Physical Vapour Disposition (PVD) the preferred method of coating.

Demographic changes in the market – High average age of designers currently in the industry poses a problem. When these employees retire they will leave a large gap in the knowledge bases of the individual companies in an industry where designing is very knowledge intensive. This provides several problems to the industry in terms of training and recruitment. Because of the new technologies being implemented, the materials and the design of the tooling itself, employee training can only be done in conjunction with an expert in the design of the tooling. Engineering in general is suffering from attracting high calibre individuals and this also the case in the cutting tool industry. Salespeople and the technicians in the field, the ones who spend much time with the customers must be knowledgeable enough to ensure that the most appropriate tool is selected for each particular task.

Environmental Issues – The process of cutting metal generates heat and this is cooled by the use of cutting fluids and this environment can be very dirty. The future is a call for cleaner machining and providing greater emphasis on the recycling of tooling. This will require a change in the way we the companies do business and require a different mindset to cope with a change in attitude.

This section has highlighted the main challenges for the UK cutting tool industry and in the next section the author discusses the effect of these challenges and the measures being taken to overcome the challenges in the industry by Widia Valenite UK.

1.2.5 The Strategic Position of Widia Valenite UK

The major strategy of Widia Valenite is to go out and get any business that they can together with a change to provide more standard products than the special tooling that is currently the business. Company structure and culture are of concern with the lack of direction from the German parent company after a consolidation five years ago. A concerted effort to gain more business in the aerospace sector is under way and is a major strategic plan. Widia Valenite provides a design and technical service only in the UK. The designs are manufactured by subcontractors in the UK and sometimes by the parent companies in Germany and the United States.

The trend of greater integration with customers and distributors is mainly from the automotive industry that requires the tool manufacture to take-over complete projects. The kind of interaction at all levels of the organisation or 'key account management'. Widia Valenite does not have the tool management products or the infrastructure to handle this new customer/manufacturer integration where the manufacturer of the cutting tools takes up shop in the customer's facility providing round the clock tooling. Rather it would have to run projects in conjunction with its distributors. For suppliers, this means channel conflicts. Manufacturers have to ask how they can support various forms of integrated supply, and still provide much higher levels of technical support than ever before. Many integrators have the logistics, but not the necessary product technical expertise; as the degree of necessary product expertise increases as products become more complex.

There is a demographic change in the market, with designers of cutting tools having high average ages, which causes concerns for all players in the industry. Widia Valenite have made an effort to address the problem of these expert designers leaving by taking on young apprentices not only to design cutting tools but also to provide a range of other business skills, such as sales, marketing etc. within the organisation. The route to being a design engineer in this industry is by apprenticeship usually between 4 to 5 years. Further steps have been taken to capture this knowledge by working with universities and hence this research project. The training they provide is good with hands-on customer orders and plenty of opportunity to visit customers to assess their needs.

However, with a small business unit and the level of design technology it is not possible to see where they can recruit high calibre engineers at this level of the business, perhaps at the parent company level. In terms of technological changes in tooling Widia Valenite through their parent company in Germany (where most of the R&D is carried out) do provide innovative solutions to their customers and it is provided relatively quickly to the customer. Due to the distance between the parent company and the base in the UK it is not done quite as well as the Sandvik's & Kennametal's of this world who seem to be ahead of Widia Valenite on this front. Closer communication with the German parent company is needed to provide faster and more customer orientated product innovation.

This section has discussed the strategic position of Widia Valenite within the UK cutting tool industry and examined the measures it has taken to overcome challenges presented. The next section describes the cutting tool design environment examining the nature and extent of cutting tool design.

1.3 CUTTING TOOL DESIGN

The research was carried out in collaboration with Widia Valenite UK through the Engineering Doctorate (EngD) programme. The UK site is a special purpose cutting tool design service primarily for the automotive and aerospace industries. The design process begins with the initiation of the design by a proposal via a salesperson. With this initial specification the designer can then search for the closest few designs, which are similar in nature to the new proposal. This becomes a case of redesign, modifying existing designs to provide a full manufacturing drawing. Throughout each stage of the design process the designer accesses various items of knowledge in order to achieve the final design. The design does not take place in a vacuum; the designer has to consider many aspects in the product design and as such the design of cutting tools is complex and knowledge intensive.

Metal cutting is a dynamic technology, involving several disciplines of science. It is continually changing in line with strategies, material developments throughout the manufacturing industry worldwide, and also the developments within the metal cutting industry. The competitive challenge here is the continual provision of improvements to metal cutting production, thus leading to a race to provide better tool materials, cutting edge geometries and methods of tool-holding. Metal working know-how and skill can be traced back many centuries. However, the metal cutting we know into today's industry began with the industrial revolution of the eighteenth and nineteenth centuries and accelerated during the twentieth (Sandvik Coromant, 1994).

Cutting tools range in complexity from the simple single point tools such as turning tools to multi point tools such as a milling cutter. The purpose is to remove material from a component or surface to achieve a required geometry, e.g. the machining of a casting. Examples of turning and milling cutters are given in figures 1.1 & 1.2 respectively. Typical components of a cutting tool include an insert, shim seat, clamp, screw and shank (backend) as shown in figure 1.1.

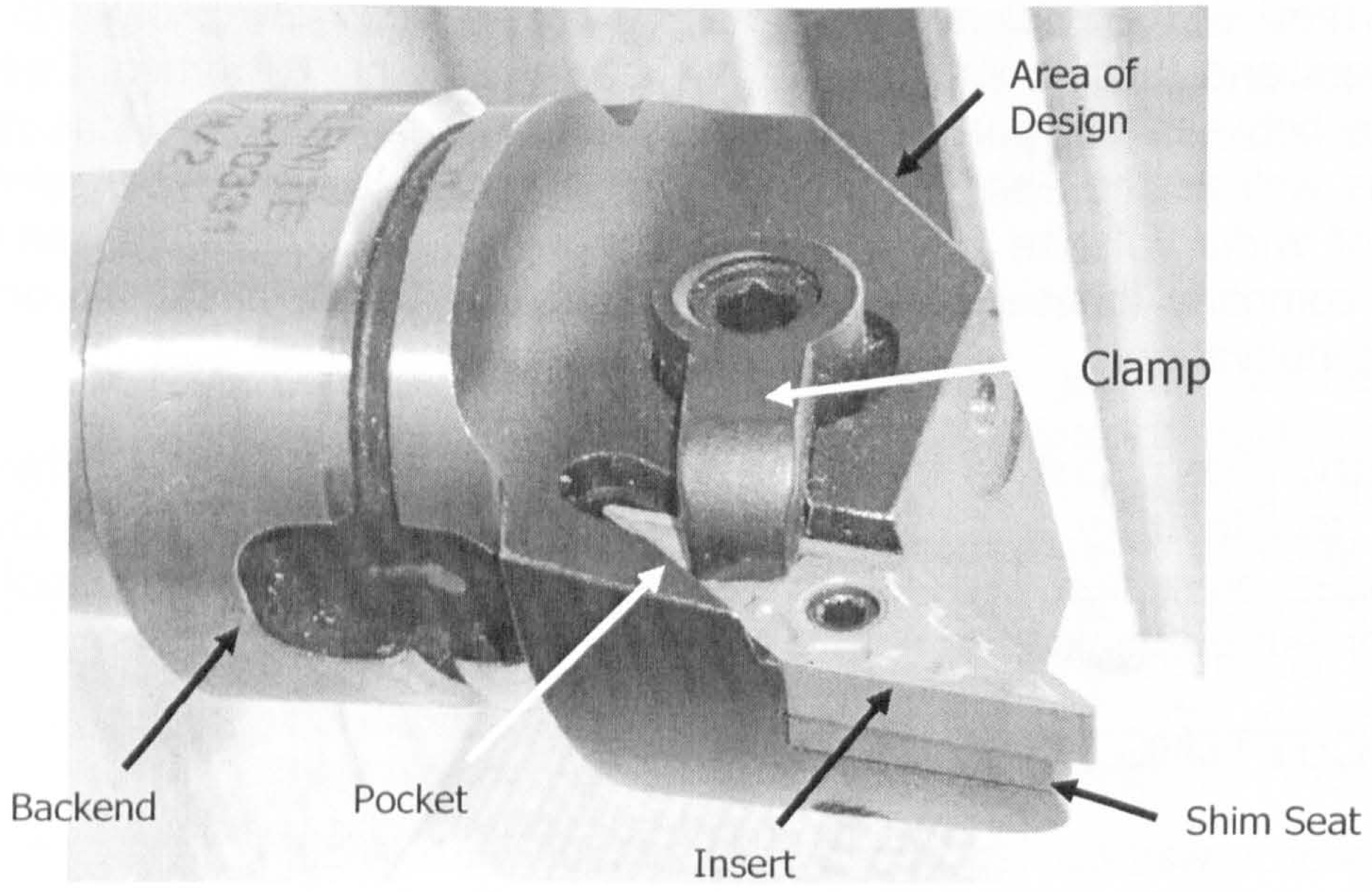

Figure 1.1: An example of a turning tool.

For the turning tool shown in figure 1.1, a 'P-system' clamping mechanism is used, and the type of clamping/holding mechanism depends on the application. The tool shown in figure 1.1 is a turning tool, which is designed and manufactured to machine an undercut on a camshaft. The backend of the tool is a standard DIN69893 fitting (the dimensions are standard and are available on microfiche) and as such is explicit. The actual design is carried out on the insert pocket and the shape of flank to meet the dimensions of the component avoiding any interference with the component. Special attention is paid to the design of the insert pocket to ensure dimensional accuracy.

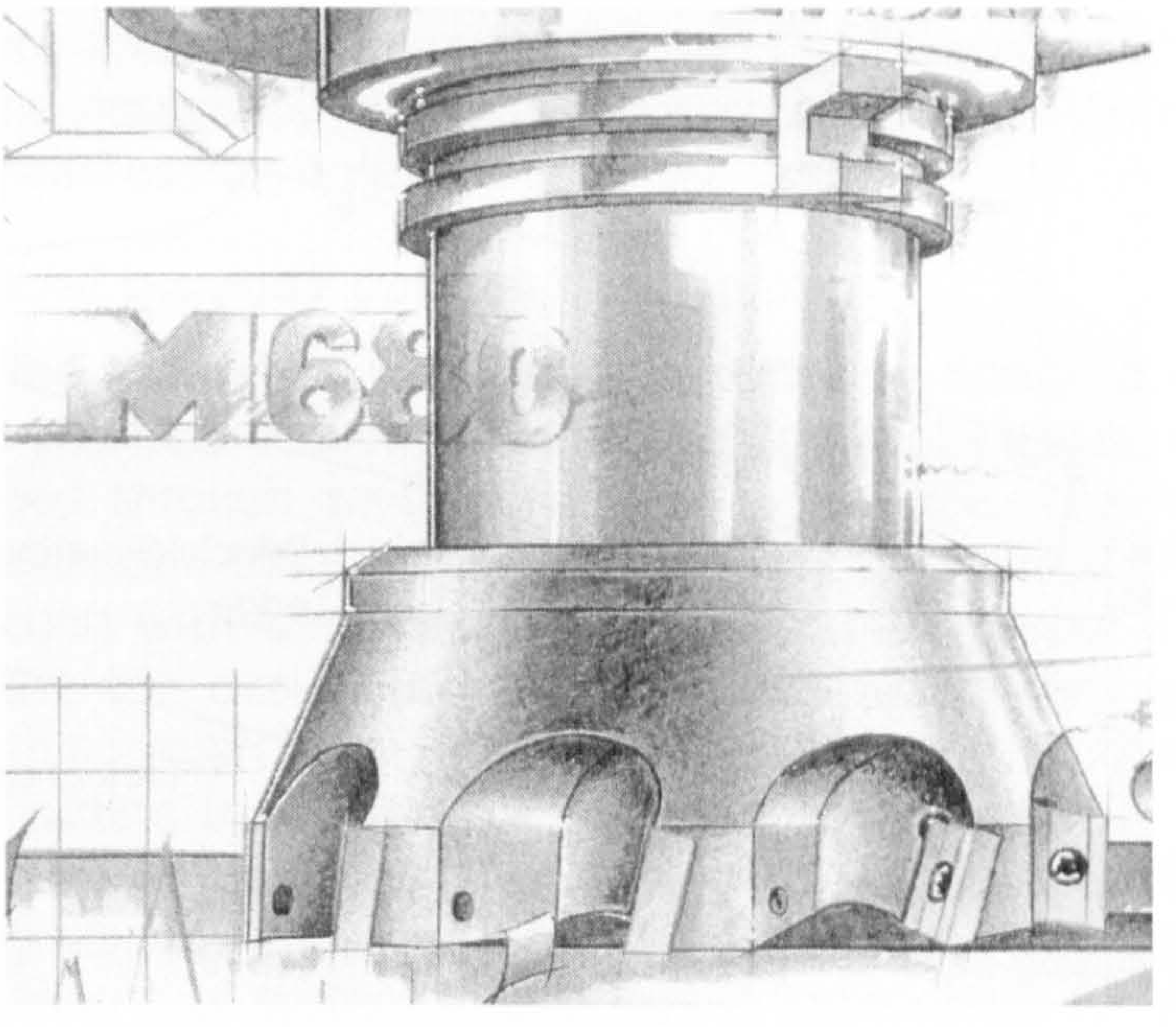

Figure 1.2: An example of a milling tool.

1.3.1 Theory of metal cutting

The theory of metal cutting can aid in the design of a standard cutting tool. However, it is the central argument of this thesis that in industry practical knowledge of how special purpose cutting tools behave in their operating environments is invaluable. Nevertheless, a certain amount of theory about cutting tools needs to be understood in order to design a technically viable cutting tool. Although it is possible to use textbooks to teach the rudimentary tool design to a novice (Bhattacharyya, 1984; Chattopadyay, 1997), there are many instances when specific knowledge of the expert incorporates specialist knowledge of the designed products, which has been gained over the years. For example, it is possible and necessary to understand the principle features of a cutting tool as shown in figure 1.3.

The key factors for the machining industries in developing machining strategies are to reduce the *actual cutting time* (T_C) and increase Metal Removal Rate (MRR). The actual cutting time T_C refers to the time required to machine a bar from an initial diameter, D_i to a final diameter D_f in a number of passes (Chattopadyay, 1997). The factors affecting T_C and MRR are the Cutting Velocity (V_C), Feedrate (s_o) and Depth of Cut (t). Typically, industrial cutting tool design (V_C) and (s_o) are given in the form of constraints by the customer machine capabilities; thus the cutting tool designer will design according to the depth of cut that is required. The designer will then match an insert to the depth of cut and also consider the other two factors concurrently.

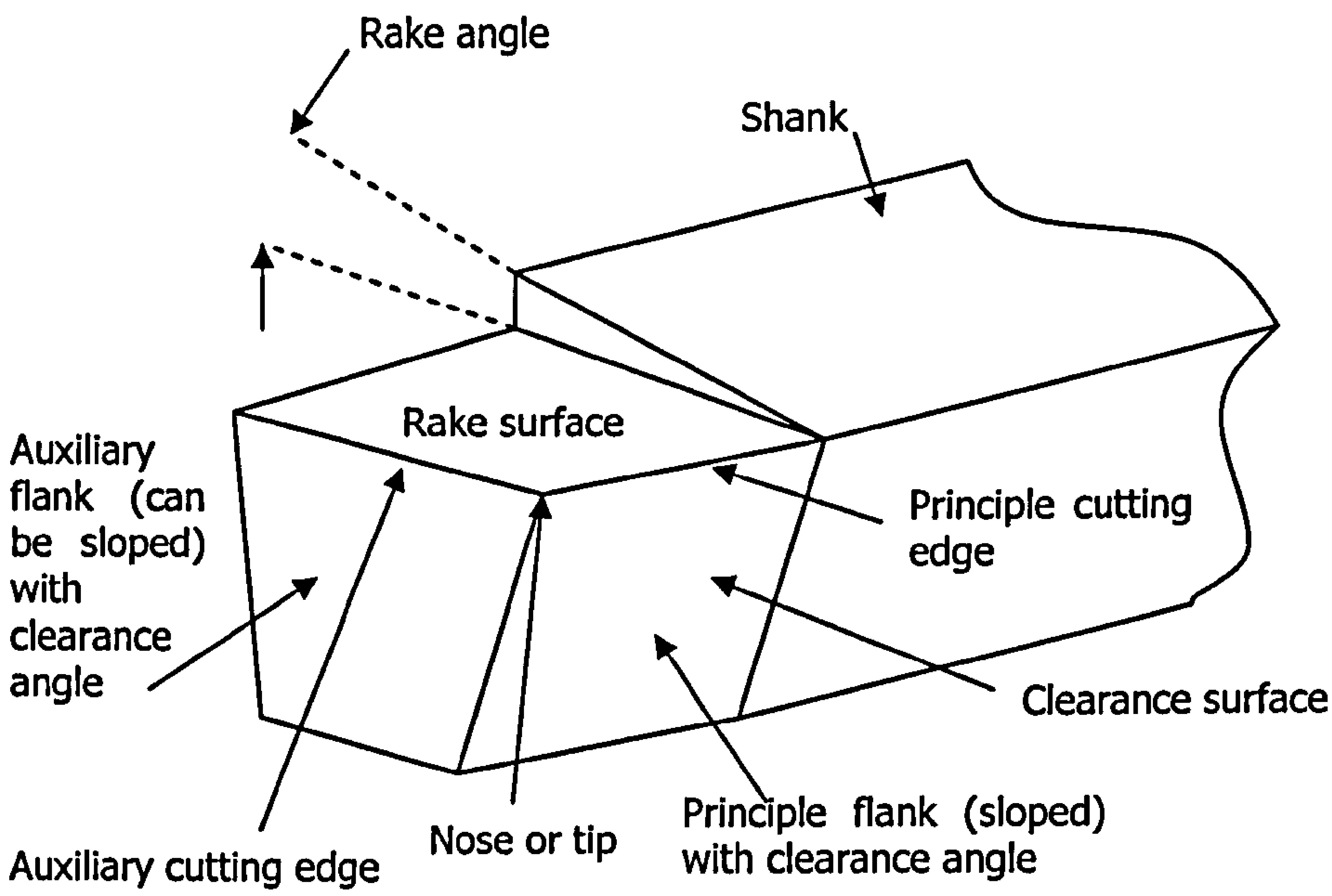

Figure 1.3: Principal features of a cutting tool (Chattopadyay, 1997).

Cutting tools and conditions selection is a complex task, which requires considerable experience and knowledge. The objectives of any tool selection exercise are to select the best tool-holder(s) and insert(s) from available cutting tool stock, and to determine the optimum cutting conditions (Arezoo et. al, 2000). This selection process is undertaken with the aim of increasing productivity, quality and economy and so that the following four questions can be satisfied:

- Is it technologically acceptable?
- Is it technically viable?
- Is it economically viable? and
- Is it environmentally viable?

Cutting tool theory provides the basic knowledge required by the designer when designing cutting tools. However, practical knowledge or know-how gained over a number of years of experience is essential in the industrial setting. For example, the know-how, which enables the designer to assess, qualitatively the success or failure of a special cutting tool design is not available in any textbook and is located within individuals as separate islands of experience. The next section describes the differences between standard and special cutting tools.

1.3.2 Standard versus special purpose cutting tools

Standards have been researched, designed and tested to perform under specified conditions and environment. If a standard tool is selected for a particular condition and environment and the right combination of insert/material selection is made then the standard tool will perform as it was intended. Whereas, the special purpose cutting tool design is a "one-off" that is not tested before it reaches the customer and can behave in an unpredictable manner. It is the designer's job to understand the complexity of design issues to prevent any failures first time.

1.3.3 The special purpose cutting tool system

In addition to the theoretical knowledge required to design a cutting tool as outlined in the previous section; practical cutting tool design requires further knowledge gained through several years of experience. The purpose of this section is to understand the principles involved in the practical design of cutting tools by interacting with the experts to identify the types of knowledge they utilise throughout the design process, including where they go to find this knowledge. In this research the mechanical system is the 'cutting tool system', defined as the cutting tool and the work-piece as described in table 1.1. The cutting tool is composed of the *tool holder*, *the clamping system* (cartridge, clamp, clamping screw), and *insert* (this includes shim seat and insert screw). Defining the cutting tool system in this way is appropriate for special purpose cutting tool designers. When considering a new design proposal a designer would very often layout the component and match the tool to this layout. Therefore both the component to be machined and the cutting tool itself play an important part in the design of a cutting tool.

Table 1.1: The special purpose cutting tool system.

System Element	Description
Toolholder	Made of steel. Its purpose is to hold and present the cutting edge to the work-piece. The element of the cutting tool system that locates the insert in place. The force from the machine tool is transmitted through the toolholder to the insert so that it can cut the component. Provides firm support for the insert.
Clamping Mechanism	This mechanism can consist of a shim seat (support insert); insert screw, clamp & screw and various other minor items. Its purpose is to hold the insert in place securely.
Insert	The business end of the cutting tool system. Generally a carbide
Work-piece	The part of the system to be cut. The insert removes material from the workpiece to achieve the shape or finish required for the workpiece to do its task.

A special purpose cutting is a one-off bespoke tool whose specifications cannot be met with a standard off the shelf tool. A special cutting tool requires the designer to take standard components and arrange them according to the requirements set by the customer. Often the tool may just require one special purpose designed component e.g. the toolholder will remain standard and the insert will change or vice versa. At the more innovative end of the design spectrum in cutting tool design; the designer would design special purpose tool holders and inserts. Many of these designs require the reuse of past designs. In the section 1.3.5 the capture and reuse of knowledge in the cutting tool design industry is discussed. But first the author defines the term "knowledge" as used throughout this research.

1.3.4 Definition of knowledge

Throughout this thesis the following definition of knowledge will apply. Knowledge is defined as: *"Knowledge = Expert – Novice"* (Bailey & Roy, 2002, Bailey & Roy, 2000). This is a working definition of the term knowledge that implies that knowledge is the difference between the expert and the novice. It has been derived with the observation that a graduate or apprentice entering the cutting tool design domain will have background knowledge in the engineering design sciences or the cutting tool industry i.e. s/he will know the basics of designing or tooling methods. However this will not allow the novice to fully participate in the cutting tool design process. There is an extra level of knowledge required that is developed over time. Thus there is a difference between the expert and the novice. The next section will discuss the activities of knowledge capture and reuse in the cutting tool industry.

1.3.5 Knowledge capture & reuse in cutting tool design industry

In the cutting tool industry, reuse of past designs is high. Often it will be the designer remembering what they have done before. Here the designer is able to recall the design task carried out and the application with little or no trouble. Therefore, if this extra non-technical knowledge can be captured as well then one would have useful design rationales, taking a global view of the design process. For instance, if in five years time a solution to a design problem points to a design undertaken five years ago, then the designer would have a complete picture of the state of the environment of that designed element. It is expected that this would improve the decision making to design the later product. Practical cutting tool design requires knowledge gained through several years of experience. However, it is not possible to deal with this knowledge without an understanding the nature of the knowledge involved. A robust framework to capture knowledge is required to facilitate its reuse. The following section describes the challenges in capturing and reusing design knowledge. The variety of the types of information required to design a product complicates the matter of capturing, and reusing design knowledge. Identifying the critical knowledge and understanding how to elicit it is a time consuming task requiring the researcher to actively participate in the design process. A suitable representation of this knowledge is required to represent the knowledge discovered and provide a suitable medium to facilitate its reuse.

1.4 RESEARCH PROBLEM

The problems faced in the management of design knowledge and design reuse are critical tasks within industry. For an organisation to remain competitive in a mature market, the factor that distinguishes two companies is the way in which they manage and reuse their knowledge assets. In an industry where the demographics are changing, there is a low employee retention rate and the shortages of new employees add to this need for managing of knowledge. The time taken to acquire knowledge and experience the range of tasks of the cutting tool design domain with an ever-increasing complexity in products and service provides further incentives to manage knowledge

In the early stages of the design process many decisions have to be made by designers without complete information of what is required. The designer has to consider many trade-offs in product design based on this incomplete information. The knowledge required to undertake such a task is very intensive and requires several years in the domain to be performed successfully. Information requirements of designers vary with the level of product complexity involved in the design. In most cases even if the artefact is perceived as having 'low complexity': it still requires a baseline level of information for a designer to design the artefact. It follows that if the perceived complexity of an artefact is high then more information is required to design the artefact. Providing this information is no trivial task either. The information provider must have: (1) an idea of what has been designed before; (2) the problems that have occurred in previous design work; (3) the problems designers have in interpreting their information supply; and (4) the missing information from the provided information. This increasing complexity of the industry products highlights the need for better communication between the information provider and the designer.

The design of special cutting tools is a knowledge intensive process requiring the designer to possess a variety of skills to use this knowledge to design a competitive product. The skills required are accumulated over a number of years and are both practical and theoretical in nature; however the practical skills often override the theoretical in an industrial context. Obtaining this practical and theoretical knowledge requires a high level of participation in the domain. This can prove a difficult task for someone new to the cutting tool industry and experts alike. The problem becomes one of remembering past design cases, understanding why they were designed in a particular way, and knowing where the designs can be found. It is currently unknown in the cutting tool design domain how these knowledge types interact, their structure and how the expert designer utilises these knowledge types to design the product. This represents a significant gap in the knowledge of cutting tool design.

Therefore, the aim of the thesis is to develop methodologies and frameworks to elicit, formalise and reuse key knowledge in the special purpose cutting tool design process.

1.5 STRUCTURE OF THESIS

To achieve this aim the thesis is structured as shown in figure 1.4, annotated to describe the flow of the research.

Chapter Two, The Capture & Reuse of Design Knowledge: Details the literature review, which examines the capture and reuse of design knowledge. A review of the methods and models of design is given highlighting the special nature of design knowledge. The chapter highlights the problems of capturing and reusing design knowledge; followed by a review of the tools and techniques that are available to capture and reuse this design knowledge.

Chapter Three, Research Design: States the objectives in response to the results of the background and literature review chapters to solve the research problem. The chapter then defines the overall methodology used throughout the research to answer the problem. The chapter is concluded by key findings in the selection of a methodology to satisfy the objectives.

Chapter Four, Knowledge = Expert – Novice (KEN): A novel methodology for Knowledge Elicitation, which involves participation in the domain of application. The methodology is described including motivations for its development with a review of the use of social science techniques in engineering design. This approach is validated by four case studies; three within the cutting tool industry and an example from cost estimating. Finally, in conclusion the usefulness of KEN is examined against other knowledge elicitation methods.

Chapter Five, Knowledge requirements for special purpose cutting tool design: The capture of the knowledge requirements of cutting tool designers. This chapter highlights the initial knowledge capture activity by active participation in the design process with the KEN methodology. The knowledge requirements are categorised according to whether they are internal, external or technologically based. The chapter then concludes with summary and key observations.

Chapter Six, Developing an ontology based framework for the representation of cutting tool design knowledge: This chapter describes the development of an ontology to formalise cutting tool design knowledge using a Function-Behaviour-Structure approach. The ontology provides a set of vocabularies for the ways of achievement of a set of functions for special purpose cutting tool design. Highlighting the key observations in the ontology development concludes the chapter.

Chapter Seven, Implementing a viewpoint of design reuse: This chapter describes the development of a Case-Based Reasoning technique to retrieve similar past cases to reuse in the solution to a new problem. Using the set of terms described in chapter six, ninety-six design cases have been implemented into a case base. The validation of the viewpoint implementation is by case study and questionnaire. Implementation issues are then considered for the reuse system in the sponsoring organisation. Finally, the chapter is concluded by drawing upon the experiences of the work carried out in implementing the viewpoint.

Chapter Eight, Discussion, Conclusions and Future Work: The research findings are discussed. The advantages of the proposed system to capture and reuse cutting tool design knowledge over previously published methods are highlighted with reference to the research objectives. The use of the development process to other cutting tool design areas is discussed. The business benefits are then discussed with regards to organisational learning. The chapter closes with the contribution to knowledge including the limitations of the research. The work in relation to the achievement of the objectives is examined, and opportunities for further research are presented.

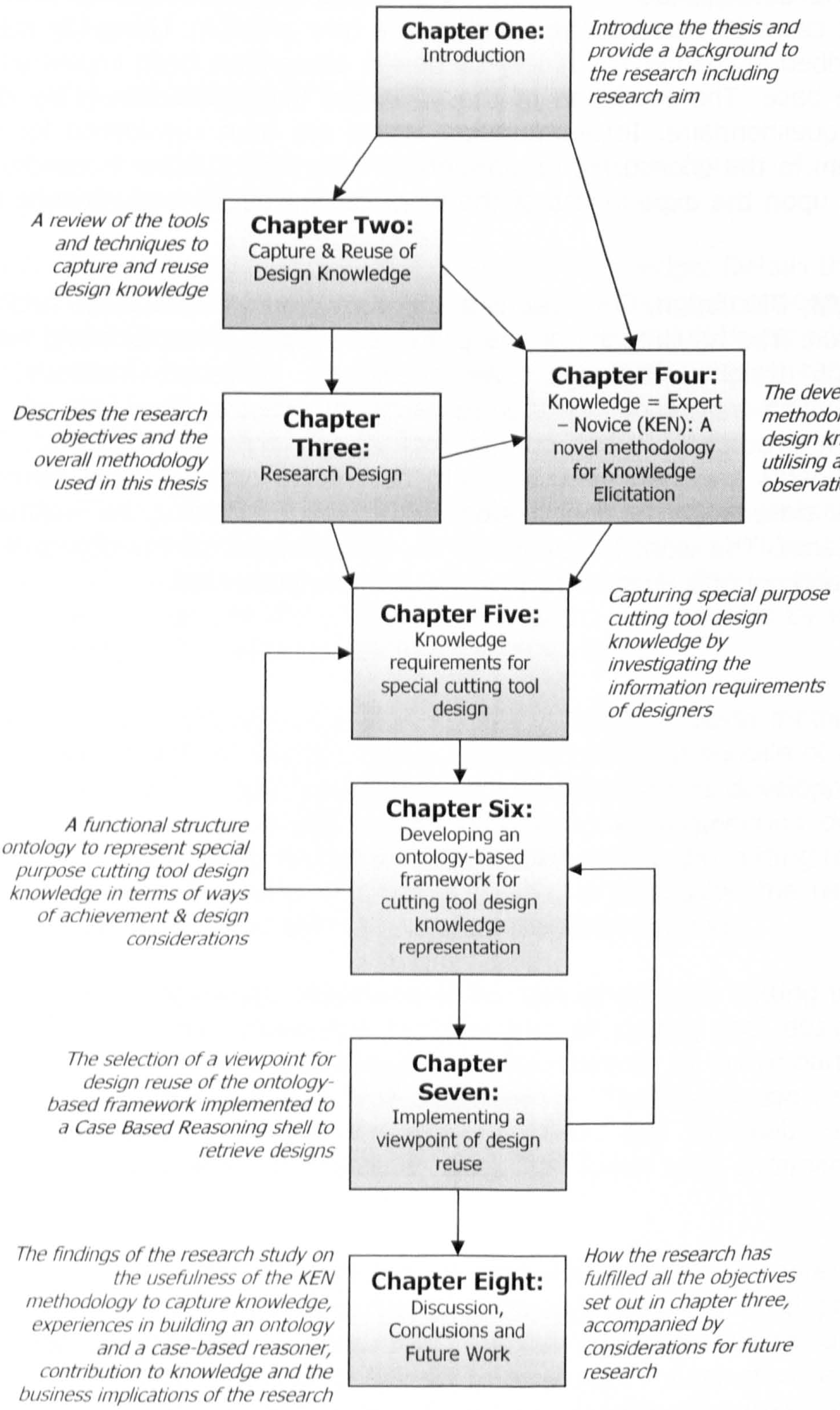

Figure 1.4: Thesis structure

CHAPTER TWO

The Capture & Reuse of Design Knowledge

2.0 INTRODUCTION

Chapter one has introduced the problems associated with the design information and knowledge requirements in special purpose cutting tool design. It has been described as a knowledge intensive task. The literature has not dealt adequately with the nature of special cutting tool design and the need for a common understanding approach to the language in the domain. The purpose of this chapter is to investigate methods for the capture and reuse of cutting tool design knowledge.

To achieve this purpose the author illustrates the state of the art in capturing and reusing design knowledge. Section 2.1 discusses methods and models of design and argues that these provide a structured approach to design but fail to meet the needs of industry based design processes. In section 2.2 problems associated with design knowledge capture are identified followed by the description and evaluation of knowledge elicitation techniques in section 2.3. The frameworks to formalise or represent knowledge are given in section 2.4. In section 2.5 the methods to reuse design knowledge are described. Finally the key findings from this review are given in section 2.6.

2.1 DESIGN METHODS & PROCESS MODELS

Design is an integral part of any product or process. Designers go through a number of processes to achieve the final specification from an initial list of requirements known as a design brief. The designer will solve problems through the design search space by a process of divergence and convergence to the eventual solution. Several iterations can be undertaken to find a solution that is acceptable. Final communication of a design is often in the form of drawings and depending on the complexity of the design, a full-scale model of the artefact could be made.

The design process has received the attention of the design community for many years and many authors have attempted to provide maps or models of the process of design (Pahl & Beitz, 1984; Evboumwan et al., 1996). These either describe the activities involved in the design process (descriptive models) or prescribe (prescriptive models) showing how to perform the activities in a better way. A more recent addition to design models have been the computational models, which emphasise the use of numerical and qualitative computational techniques, artificial intelligence techniques in conjunction with computing technologies (Finger & Dixon, 1989; Cross, 1994). Design methods can be regarded as any procedures, techniques, aids, or 'tools' for designing (Pugh, 1990). They represent a number of distinct kinds of activities that the designer might use and combine into an overall design process.

The design models

Design models are the representations of philosophies or strategies proposed to show how design is and may be done (Evboumwan et al., 1996). Three classes of models can be seen to emerge – prescriptive, descriptive and computational models.

Prescriptive models of design

Prescriptive models of design are associated with the syntactic school of thought and tend to look at the design process from a global perspective, covering the procedural steps (that is suggesting the best way something should be done). These models tend to encourage designers to improve their ways of working. They usually offer a more algorithmic, systematic procedure to follow, and are often regarded as providing a particular design methodology (Cross, 1994). They emphasise the need to understand the problem fully without overlooking any part of it and the 'real' problem is the one identified. They tend to structure the design process in three phases – analysis, synthesis and evaluation. An example of a prescriptive design process can be found in Hubka (Hubka & Eder, 1995; Hubka, 1982; Hubka & Eder 1988).

Descriptive models of design

Descriptive models are concerned with the designers' actions and activities during the design process (that is what is involved in designing and/or how it is done). These models emanated both from experience of individual designers and from studies carried out on how designs were created, that is what processes, strategies and problem solving methods designers used. These models usually emphasise the importance of generating one solution concept early in the process, thus reflecting the 'solution-focused' nature of design thinking (Cross, 1994). The original solution goes through a process of analysis, evaluation, refinement (patching and repair) and development (Evboumwan et al, 1996). Finger & Dixon (1989) further suggest that these models build models of the cognitive process – a cognitive model is a model that describes, simulates, or emulates the mental processes used by a designer while creating a design.

Computational models of design

A computer-based model expresses a method by which a computer may accomplish a specified task (Finger & Dixon, 1989). A computer-based model may in part be derived from observation of how humans think about the task, but this does not have to be the case. Often computer-based models are concerned with how computers can design or assist in designing. The former include those that make decisions and those that assist in the design process provide some kind of analysis (provide information on which design evaluations and decisions may be based). Finger & Dixon (1989) suggest that computer-based models are specific to a well-defined class of design problems. These are parametric, configuration and conceptual design problem types.

> *Parametric* – the structure or attributes of the artefact are known at the outset of the design process. It then becomes the problem of assigning values to attributes, which are called the parametric design variables.
> *Configuration* – or structure design, a physical concept is transformed into a configuration with a defined set of attributes, but with no particular values assigned.
> *Conceptual* – functional requirements are transformed into a physical embodiment or configuration.

Computational methods focus on mapping function into structure and investigate which are intended for computer implementation. Within these models design is considered to be a process that maps an explicit set of requirements into a description of a physically realisable product, which would satisfy these requirements plus implicit requirements imposed by the domain/environment (Evboumwan et al, 1996).

Design methods

Design aids, tools and support systems are used in order to arrive at a realisable product and/or process. Design methods generally help to formalise and systemise activities within the design process and externalise design thinking that is they try to get the designer's thoughts and thinking processes out of the head into charts and diagrams. There are several techniques, which enable the designer to explore design situations (literature searching), search for ideas (brainstorming), explore the problem space (interaction matrix) and evaluate designs (ranking and weighting). A fuller description of these and 35 other methods can be found in (Cross, 1994, Jones, 1981).

The models presented here and in the literature do provide a logical approach to the design process which encourages designers to articulate the decisions; strategies that they undertake to achieve a design or artefact. However, many do try to overcomplicate the design activity by providing too detailed a description of the processes in the models. The argument stems that if a designer is constrained to a particular model, then the creativity that is inherent in any type of design (engineering, industrial etc.) is lost. Most of designing is a mental process - that is the design is often done in the head. The models enable designers to provide a visual record of the processes that they undertake to achieve a particular design, along with the sketches and drawings that are also produced. This provides a series of rationales of why particular routes were taken in order to produce the artefact.

The problem with this mental picture of designing is that the knowledge and experience that a designer brings to the organisation remains with him or her.

This can be potentially damaging to the organisation as the designer may leave or retire. Marsh (1997) states that to exploit the experience of the designer throughout an organisation one must formally capture and represent the knowledge.

2.2 DESIGN KNOWLEDGE CAPTURE

There is a need in industry to capture the knowledge held by expert designers. This need is made worse by the fact that the it takes several years to begin to be able to design with any proficiency and many more years to each achieve expert status. However this situation is hindered by the poor retention of expert designers and the poor rate at which the younger designers are arriving into the industries. The need to capture knowledge stems from these issues together with the amount of time for a novice to learn from an expert designer.

The development of decision based computer support requires the capture of knowledge. This may sound simple but in fact it is a difficult and time-consuming task, as the design knowledge exists as facts and rules that are applied during the whole design process. These facts and rules can be taught to a certain extent but the experiences of the author suggest that true practice cannot be taught but has to be learnt and experienced through training by actually designing. This is often further complicated by the fact that the knowledge is often accumulated over a number of years and exists as small communities of knowledge in particular areas. Without communication and interaction this knowledge would never come out but remain implicit. If these separate islands of knowledge could be accessed then value would be added to the design process. This is particularly the case for past designs on which a great deal of time and money has been spent and therefore the reuse of this knowledge the efficiency of the design process will be enhanced.

The characteristics of design knowledge stand in the way of its capture. The first characteristic is the identification of the types of knowledge that are required by the support system and the eventual user, which by all means is not an easy task. The largest bottleneck in the capture of design knowledge is the elicitation from domain experts. The different designers have their own domain specific language for the tasks that they perform on a day-to-day basis making the task even harder. In effect they have their own categorisation of the knowledge that they use. In fact there many different views on the term knowledge within industry, which makes the knowledge capture even more difficult from the expert. In the next section a number of definitions for knowledge are given.

2.2.1 Definition of knowledge

In order to formally represent knowledge one must first define what one means by the term knowledge. For this thesis the definition *"Knowledge = Expert - Novice"* has been defined as the difference between the expert and the novice (see chapter one, section 1.3.4) and is used throughout this thesis. In this instance the novice is defined as "someone who is new, a probationary member, and there has been some 'minimal exposure' to the domain (Hoffman, 1998)." The author distinguishes this further for the KEN method by addressing the fact the author who has a background in mechanical and manufacturing engineering, has had the 'minimal exposure' to the domain. However he requires further assistance from the expert in order to design cutting tools. This is because the author does not understand the full use of knowledge within the cutting tool design domain. Thus the author defines the novice as follows:

> "A person who is new, a probationary member, who has had some 'minimal exposure' to the domain but requires further assistance from the expert to perform tasks."

This definition of "novice" aids in the explanation of KEN. There is a gap between the academic theory of cutting tool design and the practical design of cutting tools. The author recognises that there are very definite equations for the design of cutting tools as mentioned in chapter one and chapter two of this thesis. However, what is interesting is with this formal knowledge there is plenty of informal knowledge that goes with cutting tool design. This informal knowledge is built upon the formal knowledge and consists of for example: how to align the insert pocket or how to align the shim seats for which there are no formal equations. However this is fundamentally important to achieve customer requirements. The KEN methodology allows the author to capture this informal knowledge, which is tacit within the designer's mind, through observation and participation. This means that the novice undertakes the task of the expert and as difficulties arise the novice relies on the expert to provide the knowledge to solve the difficulties. This is a common method to learn a task within industry where the knowledge is multi-disciplinary being a combination of technical and commercial knowledge. This knowledge is learnt through observations and apprentice schemes and hence the people learn by doing. The author has emulated this through the KEN methodology to capture in depth knowledge.

However this is not the only definition for knowledge and the author sought the definitions from both academic and industrial sources for the term knowledge. An academic view of the term knowledge is (Schreiber et al., 2000):

> *"Knowledge is the whole body of data and information that people bring to bear to practical use in action, in order to carry out tasks and create new information".*

The industrial view is quite different from an academic view. The views tend to relate the development of knowledge through a process of trial and error in performing a task. That is, if a task is performed and whether the result is good or bad, one can learn from the situation. Typically, the cutting tool industry views of knowledge are:

> *"...to have the necessary information, or knowing where to find the necessary information to allow you to perform a given task"* (Expert from Kennametal Hertel Ltd).
>
> *"...something you learn a lot by doing something and seeing if it is the right or wrong thing to do and slowly the mind is filled up by these do's and don'ts"* (Expert from Sandvik UK).

In conclusion the author suggests that these definitions of knowledge offer different and complementary views of the same reality. The next section examines the types of knowledge in design and emphasises the types of knowledge found in cutting tool design.

2.2.2 Types of knowledge in design

The types of knowledge are defined as follows (Rodgers et al, 2000; Hubka & Eder, 1995):

Explicit or implicit knowledge

Explicit knowledge is often considered that which is written down. Implicit knowledge resides in the head of the expert. The problem with this type of knowledge is that often the expert doesn't know how to express the knowledge he or she uses on a day-to-day basis – it has become second nature to them.

Declarative or procedural knowledge

Procedural knowledge refers to how to perform a task, such as the actions and decisions that drive the design and manufacture of products. Declarative knowledge is factual information and knowing what to do.

Heuristic/algorithmic

Heuristic knowledge refers to problem solving methods that are utilised by experts which have no formal basis or can be regarded as a 'rule-of-thumb'. An algorithm is a set of steps, which will lead to a solution, if one exists. The heuristic knowledge is often regarded as 'shallow knowledge' as the heuristics often ignore the formal laws and theories of a problem. Thus the level of knowledge an expert can have about a particular domain can be either 'deep' or 'shallow', shallow knowledge occurs when an expert has a superficial surface knowledge of the problem, whereas with deep knowledge and expert has full thorough grasp of the basic fundamentals of a problem.

It is argued in this research that a designer in special purpose cutting tool design will use more heuristic based knowledge to solve the design problems. In the next section the role of knowledge within design is discussed.

2.2.3 Role of knowledge in design

Design is a decision-making activity that is complex and knowledge intensive in all engineering design processes. At each stage of the design process decisions are made based upon the experience of the designer and the organisation. The role of knowledge in design is to provide the designer with necessary information about products, processes to make the decisions and to solve problems based on the specifications given. This knowledge can be domain dependent or independent of domain. Domain dependent knowledge is the component descriptions, equations, functional knowledge etc. It is the specific knowledge to the domain in which the designs are created e.g. special purpose cutting tools. The knowledge provides the designer with information about the components and how they fit together. Domain independent knowledge is problem-solving support, which is not sensitive to the domain in which the design operates. The next section discusses the role of knowledge in design reuse.

2.2.4 The use of knowledge in design

It has been highlighted that designers spend a proportion of their time searching for information. Many authors suggest the as much as 30% of the designer's time is spent searching for and accessing design information (Cave & Noble, 1986; Lowe et al, 1999). In a typical design process the method of transferring information (design requirements) to a designer is critical to the successful design of the product. It is accepted that in engineering design, the task of capturing the design requirement is an important and difficult part of the design process (Darlington et al, 2001). The development of new products requires a large amount of information to be supplied (Macleod et al, 1994); and providing this information in a timely and relevant way is vital to this success (Rodgers, 1997). The increasing technical complexity of products and the increasing market pressures to deliver products has led to the lack of knowledge and information awareness amongst organisations having implications for productivity. This requires that future information provision will have to be handled in a more structured way (Court, 1998a; Court et al., 1998b; Court, 1997).
Many authors have investigated the usefulness of information provided and the identification of important information in design (Khadilkar & Stauffer, 1996; Kuffner & Ullman, 1991; Baya et al, 1992; Baya, 1996). Kuffner & Ullman with the aim of identifying the design information designers are interested in; provided designers with a set of documentation and recorded the inquiries using protocol analysis of the designers requesting further information due to uncertainty and conjecture. These inquiries were transcribed into questions and studied to evaluate the classes of information that the designers were interested in. Similar work was carried out by Baya et al & Baya; their approach was to classify the information requests of two designers with two & ten years design experience (with an expert present) to solve a redesign problem. Again protocol analysis was utilised and the questions raised by the designers were

reformulated into a complete set of questions by filling in missing information from context. These questions were organised into a question framework consisting of 4 categories. Khadilkar & Stauffer sought to identify and classify the design information provided and provide a means to capture the designer's understanding of the information provided in response to the questions the designer has about the original design (Khadilkar & Stauffer, 1996). Here a question-asking protocol was used; this is intended to only record the questions asked by a designer during a design session. Khadilkar & Stauffer used much of the framework developed by Baya et al to analyse their results.

However, their works differ from the proposal described in chapter five of this thesis, as the author is not asking the designer or salesperson to design an object. The salespersons were asked to assess the level of perceived design involvement that they considered the designers would undertake upon receipt of the proposal form. The designers were asked to identify the knowledge required that was not supplied within the proposal documentation. It is quite natural to ask a question when the answer is not known, the reply often yields the knowledge to solve the problem or design. The central theme here is what are the information requirements for the designer to perform his/her task. The central tenet of this study and other studies mentioned look to the designer and the problems faced by the designer when presented with a design problem. The questions raised by the designer are considered to be the important knowledge required to design the product.

2.2.5 Problems related to capturing design knowledge

Design knowledge, is in general, comprised of descriptive information, facts and rules. These are mainly derived from training, experience and general practice. Most design knowledge is vague and lacks order and is therefore difficult to capture, store and disseminate (Edwards & Murdoch, 1993). Furthermore, the knowledge is often accumulated over a number of years (Rodgers & Clarkson, 1998) and most of the knowledge exists as separate 'islands of knowledge' (Hubka & Eder, 1995). The problem then becomes one of how to capture this knowledge and is often a difficult and time-consuming process. Artificial Intelligence (AI), and in particular micro-level knowledge capture techniques have helped to solve design problems through modelling designer activity, the representation of designer knowledge, and the construction of either systems that produce designs or systems that assist designers (Brown & Birmingham, 1997). The knowledge in design differs to that in a closely related subjects such as manufacturing as the following explains.

For example the types of knowledge of interest on the shop floor (Ravindranathan & Khan, 1999) are operation efficiency of plant and machinery, maintenance, control and raw material procurement, etc. The problem here is that the knowledge is located in many places, is of many differing topics and lends itself to different levels of precision (Ravindranathan & Khan, 1999). What are important to the designer of cutting tools are the set-up costs for tooling in order to manufacture the design artefact, reliability and quality of the work carried out in previous cases. Also the capability of the manufacturer is an important factor i.e. whether the manufacturers have the expertise and equipment to undertake the task. At the conceptual and proposal stages during the design the designer would take the manufacturability of the artefact into account. Because the background and experience of the designers are mostly based on an apprenticeship, the appreciation of what can be manufactured and the processes that are needed for manufacture are through trial and error. During observation of this small group of designers, it is worth highlighting that the designs are not 3D modelled and analysed by advanced computer methods but analysed through picturing in the head of the designer and then a through checking/verification procedure of what 'feels right'. Both design and manufacturing knowledge, however different in their categories and context of knowledge, still use the same methods of capturing and representing knowledge including the rationale as to how the process is planned the way it is (Roy & Williams, 1999).

2.2.6 Cutting tool design knowledge

The section above has highlighted the similarities of design and manufacturing knowledge. This purpose of this section is to identify the methods by which cutting tool design knowledge is used within manufacturing.

The use of cutting tool design knowledge is most prevalent in the process planning stages of the manufacturing process. This is where a process plan is created either manually or in recent times by computer with Knowledge-based Computer Aided Process Planning (CAPP) software. The need for this type of support was quite simple: the complexities of the manufacturing process in the concurrent engineering paradigm have essentially meant that the automatic generation of these process plans was necessary. A process plan is created based on a manufacturing engineer's experience and knowledge of production facilities, equipment, their capabilities, and processes and tooling which are all stored on the knowledge base. The generation of a process plan requires several types of knowledge including manufacturing engineering strategies and manufacturing know-how.

A part of this process is the selection of a cutting tool to perform the machining in the manufacturing process. The CAPP software selects cutting tools, feeds, speeds and prepares NC programmes. The knowledge bases in these cases contain knowledge about the design parameters of the cutting tool e.g. operable speeds, feeds etc. Research into the optimisation of these cutting tool selection knowledge based systems is being undertaken. This area was chosen by the author to show the closest application of the use of cutting tool design knowledge. There are however major differences between the view of knowledge that these approaches have taken and the research described in this thesis.

The first of the types of system considered selects cutting tools based on the requirements of the user. Mookherjee & Bhattacharyya (2001) have developed an expert system that selects the turning tool/insert or milling insert, the material and the geometry based on a set of user requirements. The factors that are considered in this selection are workpiece material characteristics, part characteristics, machine tool characteristics, support systems and cutting tools or insert characteristics. The knowledge is organised according to international standards for each part of the cutting tool or component material. For example, for cutting tool selection the Society for American Engineers (SAE) system is used. In the case of selecting an insert; an ISO standard is utilised. The materials of the component to be machined are organised according to one of the international material nomenclatures i.e. SAE, DIN etc. Milling inserts have been classified into three categories, and at the start of the session the user has to select the type of operation. The user selects the material to be machined which is similar to the turning selection however; the milling selection differs by asking what type of application i.e. roughing, finishing etc. and the angle of entry. A selection of inserts will be displayed if possible and the user has to make a selection. The insert knowledge is represented according to the ISO 1832-1991 specification for the designation of inserts. The cutting tools are selected by an algorithm within the inference engine that interrogates the knowledge base.

Edalew et al. describe an approach to the selection of optimal cutting tools and optimum cutting conditions to reduce cost and time of manufacturing. The system deals with cylindrical and prismatic components and different types of machining techniques. It has the ability to select cutting tools, calculate cutting parameters and estimate costs for various machining techniques (Edalew et al., 2001). A feature of this system and the system by Mookherjee & Bhattacharyya is the acquisition of knowledge. In the system mentioned by Edalew et al the knowledge has been acquired from industry & academic based literature and discussions with experts from industry. It is organised into five categories: materials, tool materials, cutting tools, cutting parameters and machining techniques. The knowledge base contains rules and techniques for knowledge representation. Information related to cutting tools and component features and machining process are represented in a hierarchy. These types of system have also been observed in industry and in particular systems such as TESS (Kennametal Hertel Ltd) which is a system that matches parameters inputted and creates a design, and systems that have been developed generically by the cutting tool industry that form databases based on cutting tool standards. There are also a range of product part catalogues that are available over the Internet (Sandvik Coromant, 2003; Iscar, 2003).

In the cutting tool industry the selection of an appropriate cutting tool plays a significant role in the machining of a component. This requires extensive knowledge. In the systems above the selection of these cutting tools is performed by a knowledge based system for decision-making. However for special purpose cutting tool design it has been observed that the designer makes use of his extensive knowledge including: *history of what has been designed before, experience of removing metal and knowing what the tools can do.* During the design process the designer would consider the technical characteristics of the cutting tool, the customer capability, and the conditions of cutting environment, manufacturing processes, economics, and strategic issues.

The difference between the systems proposed in this section and the special purpose cutting tool design is the depth of knowledge required to able to design the tool. The next section highlights other sources of cutting tool design knowledge.

Other sources of cutting tool design knowledge

The academic literature provides a basis for the design of cutting tools by providing an examination of the science behind the machining industry (Bhattacharyya, 1984; Chattopadyay, 1997). Industry based literature offers a more practical view of the cutting tool business. The publication by Sandvik (1994) provides a resource of experience-based solutions to the considerations required for the selection of tooling. This has been joined by internet based resources such as those by Schneider (2002). Again in the same vein as the Sandvik publication this offers advice aimed at material tool selection for the practical cutting tool application.

There is a lack of literature on the knowledge requirements of designers in cutting tool design. The argument of this thesis is that it takes more than just the books and a selection system for the design of special purpose cutting tools. As mentioned in chapter one the differences between a standard and special purpose tool is that the standard tool has been optimised. Having a optimised solution that includes the combination of the best components to do the job on the customer's manufacturing line requires an added dimension to the task of design that is above what is currently available from the selection of systems which have been mentioned. A standard tool which has been designed and tested for its operability will perform to those same standards if the conditions remain equivalent to that of the testing. The design of special purpose cutting tools has been observed, and at no stage were there any testing of the component prior to sending to the customer.

2.3 DESIGN KNOWLEDGE ELICITATION TECHNIQUES

Knowledge Elicitation is the process of collecting from a human source of knowledge, information that is thought to be relevant to that knowledge (Cooke, 1994). The task of knowledge elicitation is to gain some familiarity with the application domain by understanding the terms and concepts from manuals, books and in house documentation (Darlington, 2000). However, these only go so far, (sources become outdated or there is difficulty understanding the domain) and interaction with a domain expert is required. Two types of knowledge may be elicited from the domain expert, explicit and implicit knowledge. Eliciting implicit knowledge is the more difficult of the two, as this knowledge rests in the head of the expert. The problem is that often the expert doesn't know how to express the knowledge as he or she uses it on a day-to-day basis – it has become second nature to them (Bailey et al., 2000). There are various techniques of eliciting the knowledge from the expert, but interacting with expert or observing the expert in some form or another is the basis for the knowledge elicitation techniques. The complexity of the engineering environment, which incorporates a variety of knowledge sources, requires several different knowledge elicitation techniques to be utilised, as one technique cannot cover all the nuances that the design expert has to deal with. In the case of the work carried out in this thesis there is a need is to specify the terms, concepts and relationships that occur in the special purpose cutting tool design domain.

2.3.1 Similarity between knowledge elicitation and requirements elicitation

There are parallels between the process of Knowledge Elicitation (KE) and Requirements Elicitation (RE). The difference is in the person that the processes focus on. With Knowledge Elicitation, the focus is on the expert from whom the knowledge is elicited. Whereas RE one is focusing on the end user from which the requirement for the system are elicited. However the skills involved in both areas are very similar and have been examined by Byrd et al (1992). There is a need to establish a rapport with the agent[1], the ability to communicate and suggest solutions, the knack of understanding the agent's motivations or concerns and the ability to conceptually map an informal understanding to formal information architecture. This suggests that both of these fields have techniques that can be used interchangeably to carry out the elicitation process; it is this reason that in this thesis the process of KE & RE will be used interchangeably for the rest of this review of elicitation tools and techniques.

Knowledge acquisition is the process of acquiring knowledge from a human expert (or group of experts) and using this knowledge to build knowledge based systems (Smith, 1996). Knowledge acquisition and elicitation represents a large amount of the development time in the knowledge capture process. Kidd (1987) identifies two phases of execution in the acquisition of knowledge from experts. There is a communication phase and an interpretation phase. In the first phase the Knowledge Engineer[2] uses a variety of communication techniques to interact with the agents in question. Table 2.1 gives the main communication approaches to knowledge acquisition. These can be broken down into four main areas adapted from (Winstanley, 1991).

[1] The term 'agent' is used to group both end user and expert.
[2] Knowledge engineer or elicitor will be used interchangeably for someone who elicits requirements or knowledge from the agent.

In the second (observational approaches), the knowledge engineer interprets the information to draw conclusions about the knowledge or requirements. As the elicitor is interpreting the information from the expert the key factor in the quality of the knowledge/requirements obtained is the skill of the knowledge engineer. This is affected by the experience of the elicitor to perform this task and the background of the elicitor in the domain under investigation. For this research this was taken into account with the author spending several months with organisation to familiarise himself with the domain.

Table 2.1 – The main approaches to knowledge acquisition.

Direct Approaches	The knowledge engineer interacts directly with the expert to obtain an explanation of the knowledge that the expert applies in the design work.
Observational Approaches	The knowledge engineer observes the expert in the performance of the design task.
Indirect Approaches	The expert is not encouraged to try and verbalise his/her knowledge and the knowledge engineer uses other methods to elicit the information.
Machine-based Approaches	Elicit knowledge through use of either knowledge-engineering languages or through induction from databases of domain examples.

2.3.2 General considerations in knowledge & requirements elicitation

The first step in knowledge elicitation is the identification of the problem/s that requires solving which subsequently will identify where the locations and boundaries of the knowledge exist. This first step will indicate the candidates from which the knowledge will be elicited. The first step in this knowledge acquisition will allow the identification of the different types of task and scenario to which the knowledge applies. This is demonstrated in chapter four and five describing the participation of the author in the design domain.

The problem of knowledge elicitation is that who does one select as appropriate candidates from which one can elicit the information. If there are different levels of expertise within the organisation, then who is the right expert to talk too? This is very important to the types and level of knowledge obtained and the overall quality of the results obtained in the research. The identification of users should be incorporated in the elicitation process (Sharp et al., 1999). A broad range of persons in the domain should be sought when performing the knowledge elicitation. This includes expert designers, novice designers, and other employees of the organisation requiring design input into the jobs. During the participation of the author in the design domain he sought the views and experiences of designers, salespersons, management and novices in the domain to obtain broad view of the knowledge requirements of the organisation.

Another potential pitfall in the results obtained during the knowledge elicitation exercise is the elicitor's own background and the mental constructs the elicitor has about the domain, which can obstruct the views and opinions of the individuals from the knowledge, that is being elicited. This results in a biased interpretation of the domain, not reflecting the understanding of the real issues and problems faced by the individuals in the domain.

Domain individuals have their own specific languages to describe the tasks that they perform as alluded to previously. However during the elicitation process domain individuals do have difficulty in articulating their knowledge or even requirements. In these types of situation one could analyse a particular task the individuals currently perform in order to understand what their knowledge or requirements maybe. Specifically, the person eliciting the knowledge or requirements can investigate the particular working scenario of the individual to gain more specific knowledge and requirements (Jarke & Kurki-Suonio, 1998). Another method would be for the elicitor to actually perform the task that the individual performs on a regular basis. Having this new perspective on the task, the elicitor can ask questions of the individual if they are finding it difficult to solve the task. The one drawback in the second case is the time taken for this type of activity to occur.

This section has described the considerations that have to be taken into account in the design of a knowledge elicitation activity in an effort to make a decision as to the type of method/s to be used during such activity. In the next section, the need for quality communication is discussed. This will reflect on the type of knowledge or requirements that are obtained during the elicitation activity. The author suggests that the rapport has an important factor in this communication leading to a better understanding of the domain.

2.3.3 Communication and understanding during knowledge elicitation

As described above communication is a vital part of the success in any knowledge elicitation exercise. It will govern the types, levels and relevance of knowledge elicited from the expert. The communication obstacles reside in the manifestation of expert to elicitor contact or within the individuals themselves (elicitor or the domain expert). This has been discussed in the literature. Byrd et al suggest that the former case is the inability of the expert to articulate or recall (i.e. cognitive limitations) his/her knowledge during the actions or decisions undertaken during activities (Byrd et al., 1992). The later incorporates a cognitive limitation in both parties plus a lack of understanding of the language of the domain between the expert and elicitor hindering the elicitation process. Here the background of each individual is a consideration. The background of the elicitor is going to be different than that of the expert and hence a discrepancy in the comprehension of the elicitor with the domain language and terminology. This lack of comprehension and familiarity of the domain also contributes to a further problem in the expert-elicitor interface. The expert may indeed misinterpret the questions of the elicitor.

Success in the elicitation of knowledge is also highly dependent upon the elicitor's understanding of the problem space (Coad & Yourdon, 1990). The benefits of this are twofold: the elicitation process will run smoothly but also it will greatly enrich the knowledge elicitation by making it possible for the elicitor to expose and observe the little nuances that occur on a day-to-day basis that may go unobserved if the richer understanding is not gained by the elicitor. Ultimately, the result will be a more accurate and useful capture of the domain knowledge upon which thorough research activities can be built.

This section has discussed the need for effective communication to be created in the elicitation activity in the selection criteria of the elicitation technique. This will foster a richer understanding of the domain and eventually lead to more relevant and appropriate level of knowledge to be obtained and used in the description of the domain. The next section highlights the elicitation techniques considered for the work in this thesis.

2.3.4 Knowledge Elicitation techniques

This section describes the knowledge elicitation techniques that are considered for the work in thesis. This is augmented with discussion of their strengths and weaknesses from the point of view for obtaining knowledge in a participant observation situation and the assessment of the knowledge requirements for designers at the preliminary stage of the design process. Techniques for knowledge elicitation can be classified into four main areas: adapted from (Winstanley, 1991), shown in Table 2.1. Of these, the primary means to elicit knowledge have been to use a direct approach or an observational approach, which include structured and unstructured interviews, protocol analysis, and through active participation (Hammersley & Atkinson, 1995; Spradley, 1980; Ball & Ormerod, 2000).

Interviews

Structured interviews require a focus and hence need to be planned in advance and require some knowledge of the domain prior to the interview. These interviews are based on pre-planned questions or pre-planning the material that the questions are about, i.e. domain specific probe questions, generic probe questions, using test cases, event recall and group interviews (Hoffman, 1998). Structured interviewing has the benefit of generating easy to analyse transcripts, and restricts the expert to abstraction from detailed principles of the application domain (Adesola, 2000). The main disadvantages of structured interviews are the time, initial domain knowledge required by the elicitor in order to carry out the interviews. Also the knowledge may have become routine to the expert and therefore difficult to verbalise. The **Unstructured interview** which follows the form of an open dialogue between the elicitor and the expert allows an overall view of the domain to be gained and then at a latter stage a more structured approach can be taken. Thus the unstructured interview is best suited for the early knowledge elicitation sessions (Cooke, 1994). Again the time factor is a problem and its apparent lack of structure can limit its effectiveness, and also the information elicited maybe difficult to integrate due to lack of unity or inconsistencies (Schreiber et al., 2000).

Cognitive Interviews (CI) - this is a technique used for directly eliciting knowledge for the development of the case-based systems. It sets its self-apart from other techniques, as it is suitable for the elicitation of episodic knowledge that is characteristic of the cases captured in the development of a Case Based Reasoning system. It is able to capture this knowledge because of the way it is structured around five principles of memory retrieval. The first of the five principles requires the interviewing of an expert to take place in his place of employment and in this way the expert can recall his feelings as case episodes are recalled. This is referred to as context reinstatement (Moody et al., 1996). The purpose here is to reinstate physical and psychological stimuli that surrounded the first occurrence of the original case so that they can be recreated. Focused retrieval concentrates on the elimination of distracting influences on the interviewee. Distractions interfering with the process of knowledge elicitation can be physical or psychological such as noise, movement or for the latter the interruption of the interviewer. In the situation where the expert; as far as he is concerned; has exhausted his memory recalling a particular case, a principle known as extensive retrieval could be used. This is just the ability of the expert to display increased powers of recall through repeated questioning. The creativity of the interviewer to pose different questions is required in these situations. The major limitation is this case is the time it may take to retrieve a satisfactory level of knowledge capture. The last of the memory retrieval principles is that of varied questioning which uses different questions to jog the memory of the expert to recall cases. Moving from one type of question to another is the key in this technique e.g. categorical to temporal questioning.

With the five principles of memory one is premising that the forms of memory storage are both episodic and thematic. The former is stored in the memory of the expert as the event happened and with the latter the event is stored according to how it is related to other episodes of memory. This type of memory storage can be exploited by appropriate questioning. For example thematic recall will improve with a delay between the episode and the questioning. Case based reasoning relies on the thematic type of recall.

Protocol analysis is an elicitation technique that records the expert doing his/her task by written notes, video or audiotape (Schreiber et al, 2000). It is then the task of the elicitor to decode (produce protocols) by extracting meaningful structure and rules from the observations in the terms of a coding scheme. This technique requires the expert to 'think-aloud' while being recorded. The major advantage if this technique is that the actions of an expert are to be recorded. The problems faced by the elicitor are discriminating between observations and interpreting them and according them to a behaviour or knowledge type. The expert's performance can also be affected by this 'thinking-aloud' by making the expert concentrate on the report rather than the task itself. This is a direct method that relies on the ability of the expert to articulate effectively the reason as to why they are making a particular decision, and it requires that the expert remember why the decisions were made in a certain way. This poses problems with the elicitation process. Also content of the knowledge being elicited may only be a small part of the whole to perform the task. If there is a problem of the elicitor not having the understanding of the domain then protocol analysis will have its limitations but it can also aid the communication barrier that can exist between the elicitor and expert (Cooke, 1994).

Participant observation is an anthropological technique in which the observer seeks to become some kind of member of an observed group (Robson, 2002). Active participation involves the elicitor being active in the tasks of the domain. Arguments favouring this type of technique include first hand information and high face value of information. The potential pitfalls with active participation are the objectivity of the participant, unsystematic gathering of the information and distortion in the domain of being observed (Hammersley & Atkinson, 1995; Spradley, 1980).

Summary

These techniques do not suffice as single entities, such that (although useful on their own) they cannot provide efficient knowledge elicitation in current multi-disciplinary engineering domains. Rather a number of these techniques used in conjunction can provide a richer picture of the domain knowledge. Hence the current practice is to combine techniques that provide a sequential knowledge elicitation process in the form of methods or tools. The next section looks at the methods of knowledge elicitation that combine a number of these techniques in overcoming some of the limitations of those mentioned above.

XPat

XPat (Adesola, 2000) is a process driven elicitation technique that engages the experts in mapping the process and the knowledge themselves. Knowledge is elicited through inputs, process and outputs based around the $IDEF_0$ technique. It is primarily a paper based technique allowing representation of process tasks to be modelled graphically therefore avoiding the need for lengthy descriptive text. Because of this process a rich understanding of the tasks and methods in the domain is obtained. XPat is based upon three stages: pre-analysis, problem identification and collecting and interpreting the knowledge. The technique requires a direct elicitation approach with the domain experts at all stages of the process. The approach uses such knowledge elicitation techniques as structured and unstructured interviews and protocol analysis. This method can suffer the effects of poor articulation from the expert and communication problems still surface if the knowledge elicitor does not have an initial understanding of the domain. It is only applicable in a process-based environment.

PC Pack

This is a commercially available portable PC-based workbench for requirements capture (Milton et al. 1999). It incorporates an integrated set of software tools and representations, which have been found useful in a range of knowledge engineering projects. The tool allows knowledge engineers to capture knowledge from different sources, analyse multiple viewpoints and structure it in a variety of forms (Adesola, 2002). The benefit of this workbench is the common representation language so that knowledge elicited in one tool will be immediately available in another. The down side of this toolkit is the use of engineering terminologies that makes it difficult for a novice to understand and use the toolkit. The decision is what category knowledge elements should be classified into (Milton et al., 1999).

KATKit

The KATKit is a tool based upon a methodology that uses special purpose logic, which yields a method of systematically questioning an expert in order to exhaustively explore the expert's decision-making knowledge of their domain (Adesola, 2002). During the elicitation, the knowledge is 'tokenised' and recorded in special diagrams 'exceptions graphs' or 'dTree'. Recording the expert's responses into the exception graph drives the interview.

Machine Base Techniques

Machine-based knowledge elicitation tools use a computer to elicit and capture knowledge from the designer. There are several systems developed through research (Gruber & Russell, 1991), such as IDE 1. 5 & 2.0, hypermedia tools that incorporate semiformal models of the domain and design of the component. Designers are required to perform a task on a component, after that period of work they must stop and record on the system, the decisions that led to the resulting design in that period of work.

Machine learning is a branch of AI concerned with the study and computer modelling of learning processes. It offers the potential, not only to alleviate the problem of knowledge acquisition, but also to enhance a system's problem-solving performance (Duffy, 1997). The design of cutting tools is based on experience and influenced by past designs. Machine learning provides a support tool to learn from this experience and past designs by obtaining, using, and maintaining this knowledge (Brown & Birmingham, 1997).

However these techniques rely on the expert entering what decisions he thinks are pertinent for the execution of the task in question. As stated previously this could result in the right knowledge being missed as the knowledge may be tacit and be overlooked by the expert. This section has discussed the techniques and tools that elicit knowledge from users and experts. The next section discusses the formalisation of this elicited knowledge.

2.4 FRAMEWORKS TO FORMALISE DESIGN KNOWLEDGE

The previous section introduced the first of two activities in the capture of design knowledge: knowledge elicitation. This section addresses the representation techniques for the formalism of design knowledge. The purpose of this section is to identify a suitable technique for the sharing and reuse of design knowledge. It has been observed that knowledge in design exists as unstructured, ill-defined and open in the special purpose cutting tool design domain. In an order to overcome these characteristics one can apply a formalisation to the knowledge in the domain.

What is a knowledge formalisation?

Applying formalism to a domain requires the development of a single grammatical interpretation of the domain knowledge. Furthermore, a structure should be developed that arranges that knowledge belonging to the domain. De Lavalette et al. (1997) suggest that a method for the formal specification of a knowledge domain is indispensable. Thus choosing a formalism method to apply to the knowledge within special purpose cutting tool design domain is a requirement for its formalism. The distinction between this formalism and the formal representation techniques described in the next section is made here. The formalism of design knowledge is a method to structure and interpret the domain: the result of the modelling activity discussed later in this section is transferred to a formal representation for implementation onto a computer system. These are knowledge representation formalisms.

Knowledge representation

The activity of knowledge representation is the means of organising, portraying, and storing knowledge in a computer program, which leads to knowledgeable behaviour (James-Gordon, 1992) using several techniques. A knowledge representation can be considered by the roles it plays: as a surrogate or a substitute for the thing itself, an ontological commitment, a fragmentary theory of intelligence, a medium for practically efficient computation and a medium of human expression (Davis et al., 1993). There are many tools and techniques that are available to facilitate knowledge representation. Most of these tools are based around the most commonly used representation techniques such as specialised languages, logic, objects, semantic nets, frames, procedural representations and production rules (Boy, 1991). These formalisms of knowledge representation only represent the knowledge and make it machine readable. Prior to this stage an analysis of the knowledge is required; the next section describes the main knowledge modelling techniques.

2.4.1 Knowledge modelling

In the Artificial Intelligence (AI) community the capture of knowledge is viewed as a modelling activity. This modelling activity refers to the building of a computer model or Knowledge Based System (KBS) with aim of realising problem solving capabilities comparable with that of human experts (Studer et al., 1998). This section discusses the main knowledge modelling techniques.

Role Limiting Methods

Role limiting methods were developed for diagnosis and configuration tasks by exploiting the notion of a reusable problem solving method (PSM). A PSM is a generic problem solving strategy that displays a highly regular mechanism for sequencing certain classes of inferences. These provide a domain independent way of addressing certain kinds of application tasks (Musen, 1998). It is a shell method and as such comes with an implementation of a specific PSM and thus can only be used to solve a particular type of task for which the PSM is appropriate (Studer et al., 1998). A high degree of commonality is required in the application in the specific knowledge base. The method operates on a series of ten to fifteen steps carried out with a control structure at each step where application specific knowledge is required. This means that it doesn't matter the order in which actions are taken (Adesola, 2002). The method does provide strong guidance for knowledge acquisition however it does not work in every application. A tool is provided which is capable of automated knowledge acquisition serving as a problem serving system. The system also interacts with domain experts. The method developed six template knowledge models based on different problem solving tasks (Adesola, 2002).

Generic Tasks

The need for a Generic Task (Chandrasekeran, 1986) evolves from the fact that the level of abstraction of much of the work in KBS (e.g. rules, frames, logic) is too low to provide a rich vocabulary for knowledge and control. Also, these formalisms do not distinguish between different types of reasoning. The Generic Task approach proposes that knowledge systems should be built of building blocks, each of which is appropriate for a basic type of problem solving. Its main features are *"function"* (focused on the type of problems), *"representation and organisation of knowledge"* (deals with how the knowledge is structured), and *"control strategy"* (concerned with the application of the inference to accomplish a task) (Adesola, 2002). In order to solve a problem, one only needs to choose a Generic Task appropriately suited for performing a function. It is possible to select a different function to solve the problem and also a combination of functions. In this case a GT will aid the acquisition of knowledge by providing a method for the collection of knowledge according to the GT. A GT therefore proposes a methodology for the analysis, design and construction of a practical system. There is a limitation to the methodology; the lack of a facility to choose between generic tasks. The task and problem solving methods described here are embedded into the knowledge modelling frameworks described next: the knowledge engineering methodologies including CommonKADS, MIKE, PROTÉGÉ-II, and Components of Expertise.

CommonKADS

A further tool to capture knowledge includes the well-developed KADS (Knowledge Acquisition and Document Structuring) system (Winstanley, 1991), which provides an appropriate conceptual model of the domain, which can be translated into a design for the final system. It works by providing a 'template' knowledge structure to which the designer can add the elements for the particular application. This has now been taken over by the comprehensive CommonKADS methodology which develops knowledge based applications by constructing a set of engineering models of problem solving behaviour in its concrete organisation and application context (Schreiber et al., 2000). This modelling concerns not only expert knowledge but also the various characteristics of how that knowledge is embedded and used in the organisational environment. CommonKADS methodology has been applied in industry settings at Unilever (Steele et al., 2001) and more recently in the steel-making industry (Adesola, 2002). Hence CommonKADS is the prominent methodology for modelling knowledge.

The methodology distinguishes six models each capturing a specific part of the KBS domain: the task model, the communication model, organisational model, the expertise model, the design model and the agent model (Schreiber et al., 2000; Studer et al., 1998).

Task model: This model gives a hierarchal view of the tasks performed in the organisation to which the KBS will be installed. This includes the specification of which agents are assigned to the different tasks.

Communication model: This model indicates the various interactions between the different agents including information flows between the agents and initiation of the interaction.

Organisational model: This model describes the organisational structure in which the KBS is to be installed including the specifications of the function performed by each organisational unit.

Agent model: This model specifies the capabilities of each agent involved in the execution of the tasks at hand. The agent can be human or another software system.

Expertise model: This is the model in which the knowledge is modelled. The CommonKADS methodology treats this as a three-layer model: task layer (decomposition of the tasks into subtasks and inference actions), inference layer (reasoning processes, PSM) and the domain layer (domain specific knowledge).

Design model: The expertise and communication models combine to together to give functional requirements of the KBS and the design model is then developed on these requirements. The design model specifies the system architecture and the computational mechanisms for the inference actions.

An advantage of using CommonKADS is that misinterpretations and miscommunications that may arise at the elicitation stage are bypassed due to the thoroughness of the modelling process. However, the knowledge elicited is only as good as the quality and thoroughness of the elicitation technique used. In this case direct techniques like interviewing and protocol analysis, with their attendant communication problems and consequential failure to access tacit requirements, are often relied upon.

MIKE

The MIKE approach (Model-based and Incremental Knowledge Engineering) provides a development method for knowledge based systems covering all steps from the initial elicitation through specification to design and implementation. MIKE proposes the integration of semiformal and formal specification techniques and prototyping into an engineering framework (Studer et al., 1998). This prototyping process allows the integration of the expert in the development process.

The MIKE development process starts with an elicitation phase in which the knowledge is obtained through methods such as those mentioned in section 2.3. The domain specific knowledge and problem solving process elicited is informal natural language stored in knowledge protocols. These knowledge protocols are then transferred to a semi-formal representation – the structural model during the interpretation phase. This is used as a communication mechanism between the knowledge engineer and the expert to discuss the emerging knowledge structures. The structural model is the basis for the KARL model in MIKE which is equivalent to the CommonKADS expertise model. The KARL has the same structural building blocks as the structural model but the natural language texts are now represented using the formal specification language KARL. The next phase in the process is the design phase in which the formal representation of KARL (which contain the functional specifications of the final knowledge system) and extra non-functional requirements are captured ready for the implementation phase. These non-functional requirements are considerations regarding such items as maintainability of the eventual system. Finally, in the implementation phase the design model is implemented in the target hardware and software. At each of the stages of the knowledge acquisition in MIKE the expert evaluates the models created.

PROTÉGÉ-II

This modelling approach was originally developed for knowledge sharing and reuse in the medical domain, and soon after used in engineering design (Chao, 1997). It aims at the support of the development of knowledge-based systems by the reuse of problem solving methods and ontologies (Studer, 1998).

Protégé comprises both a framework and a toolkit, and supports practically every step in the development of such systems (Park et al., 1997). Protégé uses three explicit ontologies for the organisation of information into regular, well structured hierarchies: domain ontology, the method ontology and mapping ontology. The purpose of these ontologies is to structure the domain knowledge to be acquired through an ontology editor. The domain ontology describes the structure of knowledge about the domain and covers the needs of the application task including data for the problem solving method. The method ontology defines the concepts and relationships that are used by the PSM for providing its functionality. The third ontology, the mapping ontology describes the range of declarative mapping types that are supported by Protégé for bridging between classes in the domain ontology and the method ontology.

Components of Expertise

This componential framework is a structured method for the acquisition of knowledge. The framework breaks down expertise into the task and subtasks, the domain models, the case models, and the problem solving methods (Steels, 1990). It aims at a synthesis of the ideas for the description of expert systems, that is, inference structures, generic tasks, deep versus shallow knowledge and problem solving methods but also provides alot more modularity on the different components of expertise. The process for acquiring knowledge in the componential framework is a top down systematic approach as follows. A detailed breakdown of the task in terms of the problem to be solved is required i.e. diagnosis, design and so on. In a similar method to the generic task approach in that the task breakdown is based on the inputs, outputs and the nature of the task taking place. The problem solver is used to construct case models of the problem-solving situation. The case model is extended using abstract domain models on which the problem solver infers and gathers data to expand the case model. The problem solving method has a dual role: divide the tasks into sub-tasks or directly solve a subtask by consulting the domain model.

Summary

These modelling techniques are comprehensive for modelling the knowledge intensive task including the reasoning processes and hence identifying an appropriate problem solving method for the knowledge intensive task. This research is concerned with the providing of a common understanding and providing a language for sharing and reuse of the design knowledge rather than the reasoning processes, and therefore the use of knowledge modelling techniques are not considered. A more appropriate formalism is the use of ontology as a method for sharing and reuse; this is described in the next section.

2.4.2 Ontology for sharing and reuse

The term ontology has been investigated in the knowledge engineering community with one view in mind: sharing and reuse. The aim of an ontology is to capture domain knowledge in a generic way and provide a commonly agreed understanding of a domain, which may be reused and shared across applications and groups (Chandrasekeran et al., 1999). Ontologies provide a common vocabulary of an area and define – with different levels of formality – the meaning of the terms and the relations between them (Gomez-Perez & Benjamins, 1999). Several definitions of the term "ontology" have been put forward in the knowledge engineering literature. The most famous (referred to most in the literature) of these is by Gruber (1993): "an explicit specification of a conceptualisation". The conceptualisation is an abstract model of some phenomenon in the world by the identification of the relevant terms of the phenomenon and the explicit part refers to having an explicit definition of the terms within that phenomenon. Other definitions include: "an ontology is a hierarchically structured set of terms for describing a domain that can be used as a skeletal foundation for a knowledge base" (Swartout et al., 1996). This supports the authors view on the term "ontology" and for this thesis the author interprets the term ontology as: *"A structured set of concepts with attributes together with the relationships between the concepts to describe a domain".* The omission of the term "skeletal foundation for a knowledge base" is because the purpose of this work is to generate a common understanding to promote the sharing and reuse of the knowledge in the special cutting tool design domain rather than build a knowledge base. There are several different types of ontology that exist based on the idea of capturing explicitly static knowledge in a domain (Studer et al., 1998).

Ontololgies are important for two reasons. An ontological analysis clarifies the structure of knowledge within a domain by forming the heart of the knowledge representation for that domain. The ontology provides the vocabulary for the representation of that knowledge. And secondly, if one performs an analysis on a domain of knowledge one can arrive at a set of terms that include domain specific terms, functional terms and behavioural terms. By providing formalism to these terms and concepts one can develop systems, which allow sharing across that domain. Shared ontologies let one build specific knowledge bases that describe specific situations e.g. cutting tool design (Chandrasekeran, 1999). The next section describes the types of ontology that can be developed.

The types of ontology

There are several different types of ontology: domain ontologies, generic ontologies, application ontologies, task ontologies, method ontologies and representational ontologies (Gomez-Perez, 1999; Studer et al., 1998).

> *Domain ontologies* capture knowledge valid for and reusable in a given domain e.g. cutting tool design. And as such they provide a vocabulary about the concepts in the domain and their relationships together and about the theories and elementary principles governing that domain.
> *Generic ontologies* include vocabularies related to things, events, time, space, causality, behaviour, function etc and as such are valid across domains.

Application ontologies contain all the knowledge required for modelling a particular domain.
Task ontologies provide a systemised vocabulary of the terms used to solve problems associated with tasks that may or may not be from the same domain. These provide a set of terms that describes how to solve one type of problems.
Method ontologies provide sets of terms specific to particular problem solving methods.
Representational ontologies do not commit to any particular domain. Such ontologies provide representational entities without stating what should be represented.

The development of an ontology entails a rigorous and profound analysis of the domain in question. This reveals concepts, attributes, relations, constraints, instances and axioms of the domain. The results are typically in the form of an 'is-a' hierarchy of concepts with their attributes, values and relations. Additional information about the classes and their relations to each other, as well as constraints on attribute values for each class, are captured in axioms (Studer, 1998).

2.5 DESIGN KNOWLEDGE REUSE

In the majority of cases in cutting tool design, past designs are reused. A past design is selected as a place to start the next design solution. There is often a change in some part of the reused design. Matching the correct design case to provide a solution still requires the designer to perform the material, geometry and process problem; this requires knowledge. It is widely accepted that the majority of industrial design is based on variant design (Gao et al, 1998; Khadilkar & Stauffer, 1996), and in these cases there is extensive reuse of past design solutions (Smith & Duffy, 2001). Finger (1998) states that "designers may reuse a prior design in it's entirety by selecting it from a catalogue, may reuse an existing shape for a different function, or may reuse a feature from another design". The knowledge contained in these designs is reused extensively to redesign solutions. Capturing the knowledge requirements to complete this reuse successfully requires an understanding of the nature of the design domain. However, capturing knowledge during the design process is a difficult task. The next section discusses the methods of reuse in engineering design.

2.5.1 Knowledge acquisition and reuse in engineering design

There is a role to be played by Knowledge Based Design assistants to help designers with the growing complexity of modern day engineering designs (Dyabla et al, 1996). This interaction has been often referred to as the Shared Expertise Model (SEM). These types of assistant have been made possible by the development in Knowledge Based System design, machine learning and knowledge acquisition (Tecuci, 1992). An assistant is an interactive knowledge based system that assists the user by helping the user to perform tasks and monitors the procedures that are carried out by the user. Together with this functionality is ability to assist in training and facilitate the communication with others through collaboration in systems.

With the growing complexity of many engineering design domains the numbers of parameters to be considered during the design process are very large indeed. This presents the designer with a design search space that is almost infinite thus the benefit of such systems is considerable. Design assistants are composed of four modules: a design knowledge base, a propose and revise engine, a learning engine and graphical user interface. This provides the functionality on two fronts. The assistant provides a mechanism for the user during the design process and as designs develop the user can teach the assistant new practices as the domain evolves. This means that there is the opportunity for the assistant to grow and in future help the user when s/he is not able to compose a new design. There are two roles that the user plays in this process, s/he benefits from the assistant by supplying specifications to the assistant that need clarifying and then/she acts a tutor for the assistant when faced with non-routine designs due to the lack of knowledge in the assistant. Access is also given to the user to integrate the assistant's knowledge base with the aim for introducing new knowledge.

The benefits of using such a system is that it overcomes some of the difficulties associated with the acquisition of expert knowledge; regarded as one of the bottleneck stages in the development of the expert based knowledge systems. The process of this acquisition is the expert user giving the assistant examples of correct design with explanations or rationales of how and why the designs were constructed in the way they were. When the design assistant proposes a new design the expert user gives feedback therefore continually keeping the knowledge base up to date with this expert knowledge. The improvement of the knowledge base also takes place by the assistant learning the heuristics that an expert user is applying. This is demonstrated on the work of Gruber & Russell (1991). The system designs on these types of assistants have one major drawback - the time that it takes for the system to compose and provide a solution. The causes of this tardiness are the need for the splitting of the design process into different stages so that evaluations of the design can be made. The activation of the knowledge acquisition and the learning modules of the assistant also need to be activated during this splitting of the design process thus slowing of the design process. Also if any teaching of the assistant is required along the way then the design process would be delayed further.

Bhatta and Goel (1996) provide a tactic for overcoming the problems associated with the growing complexity of engineering design by proposing analogical design as a method to tackling the many different parameters in modern day engineering design. Analogical design involves the retrieval of a known design (analog) with certain similarities to the design problem currently faced by the designer (target). Parts of the structure of the analog are transferred to the target design, by this process the right design can be arrived at when a problem for a new design is faced. The problem here is that the analog designs have to be indexed in a manner that reflects the important features of the designs in question. If new cases are then also indexed in this way when stored then they will then also be available for retrieval.

Further techniques for addressing the increasing complexity in the modern day engineering design process include the utilisation of a digital library (Regli & Cicirello, 2000). These Engineering Knowledge Repositories provide the support for collaboration in engineering design. The aim of these types of system are the collation and archiving of public domain engineering data to enable research and engineering professional users to reuse it. It is common that much of the design activity calls upon the reuse of past design cases. In fact it has been estimated that 75% of many design activities comprise the use of past design cases (Ullman, 1992), thus proving the usefulness of such systems. It has been observed by the author within the sponsoring organisation that this type of system within the cutting tool design community this would be of benefit. During his participation with sponsoring organisation, it was observed that a large proportion of the designers and authors time was spent searching for designs that could be reused.

2.5.2 Case-based reasoning in design

Case-Based Reasoning in engineering design is paradigm that incorporates the analogical design ideas of Bhatta & Goel (1996) and the design repository idea in Regli & Cicirello (2000). This overcomes the complexities in the engineering design with a tool that provides a mechanism to retrieve, reuse, revise and retain a design in a case base.

When a designer is given a specification of a design, he has to work with a set of constraints, which the eventual design should fit. This depends on whether the design is over specified and thus solution cannot be reached that satisfies all of the constraints. The use of past design cases can help here. Past designs are a history of how these balances between specification and constraints have been dealt with in the past. Therefore recalling a past design with constraints similar to the new design problem can assist the construction of the new design problem. It has been recognised that humans solve problems naturally in a similar way. Designers often report that much of their work at the initial stages of a design involves the consultation of design books and contents of filing cabinets to observe how particular constraints have been dealt with in the past (Kolodner, 1993). Formal methods to allow designers to carry out analysis whereas the process of creating a new design requires previous experience on the part of the designer or failing this, access to someone else's previous experiences (Maher & de Silva Garza, 1997).

A number of authors recite the problem of indexing as being a common problem with the organisation of cases within the case base (Maher & de Silva Garza, 1997; Bhatta & Goel, 1996). The indexing of designs needs to be carried out in such way that the features describing the designs coincide with those that help identify the relevance of the case to the new design problem when recall is attempted. Maher & de Silva Garza (1997) suggest that at the stage in the building of a case base where indexing is carried out; choosing which features will demonstrate case relevance is a difficult task. This has been addressed in the thesis in chapter seven on the development of a set of natural language descriptor terms that were elicited from designers. The use of these terms would reveal the relevance of the cases that were being recalled.

It follows on from this that recall of a design from a case base should have an informal element to it (Maher & de Silva Garza, 1997). They argue that since the design activity can be often summed up as providing the solution to ill-defined problems, recall of relevant cases is unlikely to occur simply by a direct pattern matching between the past case and the new case. The generation of an alternative is a normal pattern in the nature of the design activity. There then follows a decision-making activity to assess the suitability of a design amongst these alternatives to solve the problem for a new design. In a similar way the designer should be given some latitude in the recall of past designs. An ability to browse through a number of recalled designs from the case base, which are practically relevant to the current design problem.

There are a number of approaches for the return of past design cases from the case base to the designer. For example, recall can be made according to function. The new case is described into the functions that it is to provide and then a match is made within the case base recalling similar a design case done the similarity of functions of the past cases to the new case. This approach is used by Goel (Goel, 1992) and later by Prabhakar & Goel (Prabhakar & Goel, 1998) on the design of physical devices. The matching of attribute-value pairs is the most common technique for the recall of past designs. In this approach the attribute-value pairs of the new case are compared with those of past designs in the case base and the designs are recalled according to how closely they match the new design case. The attributes are weighted according to how important they are for the eventual design solution.

2.6 SUMMARY & KEY OBSERVATIONS

The chapter began with the review of the methods and models of design. There are three types of model that tells a designer how to carry out their design tasks. One prescribes how a design should be carried out, another that describes what should be done and the final type is the more recent addition, the computer based methods. All serve the designer well in theory but in industrial based design these methods fall short by confining the designer. It was found that designers in industry rarely follow any design model strictly. The models allow the designer to provide a visual picture of the design process but lack any formal representation of how they utilise their knowledge as most of the design is done in the head of the designer.

The design activity in cutting tool design is complex and knowledge intensive and requires a great deal of experience to design a cutting tool effectively. The designers have a special ability to visualise the design, which would take a new entrant into the process several years to acquire. The amount of information that is processed increases the complexity of this process. It is these characteristics that make the design task knowledge a difficult thing to capture and subsequently reuse. This literature survey has identified the processes involved in design and the similarities in the capture of manufacturing knowledge. The main processes of knowledge have been identified and the main issues in the difficulty is the identification, elicitation and choosing an appropriate representation for the knowledge.

Knowledge is identified through a knowledge elicitation process in which the elicitor interacts with the domain expert. Several tools and techniques have been described in this literature review but all ask the expert what he is doing rather than the elicitor doing the task himself and then asking the expert for assistance when required. This has identified a need for the improvement in the way in which the design task to overcome the complexities of the design task. A method in which the new entrant into the design process can interact in the design process by undertaking the tasks of the expert has been identified. This would overcome the issues of communication between the expert and elicitor in the existing techniques by providing a common language from which to base the knowledge transfer.

The major methods for the representation of design knowledge have been presented. Amongst these the use of ontology for the representation of design knowledge seems appropriate for this research as it allows a model to be represented that provides a means for communication and sharing of knowledge. This provides a useful medium for the reuse of knowledge.

The major obstacles to the reuse of knowledge have been identified and the case for the choosing of Case-Base Reasoning as a method for the reuse of design knowledge has been put forward. The reason for this choice is the similarity of the reasoning mechanism to the reasoning of the designer. Also it provides suitable means to search for a suitable design to be reused.

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CHAPTER THREE

Research Design

3.0 INTRODUCTION

This chapter incorporates the findings of the literature review with the research problem and the aim set out in chapter one. The issue raised from these previous chapters is the difficulty in capturing and reusing design knowledge in special purpose cutting tool design. This is due in part to the knowledge residing in the mind of the experts. Furthermore, the available techniques to elicit knowledge in this context are lacking the participant observation view of a novice in the design process. Also, the formalisation of special purpose cutting tool design knowledge has not been undertaken. A gap exists to apply a framework to represent the knowledge.

This chapter outlines the research methodology that has been selected as a basis to guide the research in order to achieve this aim and solve the research problem. The chapter begins with the definition of the research objectives, which are derived as a solution to achieving the aim set. This is followed by the scope of the research in which the extent of the research is discussed. The methodology is then defined for this research, finally the chapter is summarised.

3.1 RESEARCH OBJECTIVES

The aim of this thesis is to develop methodologies and frameworks to elicit, formalise and reuse key knowledge in the special purpose cutting tool design process. A number of research issues arise as a result of this aim, therefore the objectives can be summarised as follows:

- To carry out a detailed review of literature focusing on the capture and reuse of design knowledge to identify the state of the art and gaps in the existing theory;
- To develop a methodology for cutting tool design knowledge capture by novice participation;
- To participate in the existing design practice within an industrial environment, exploring the nature and extent of the knowledge requirements of a designer during the design process;
- To develop an ontology-based framework for special purpose cutting tool design ontology in order to represent the knowledge required;
- To develop a viewpoint of the ontology for effective reuse;
- To implement the "reuse" viewpoint of the ontology in a suitable software environment.

3.2 DESIGN OF THE RESEARCH

The author spent an initial one-month in the sponsoring organisation. During this time he was able to observe the special purpose cutting tool design process. This initial duration was required so that the author could familiarise himself within the domain to allow him to participate effectively in the design process for a longer period of six months. Throughout the one-month period the author observed what was happening in the domain, asked questions within the domain, experienced the design process to identify the type of cutting tools being designed and also to build relationships within the domain in order to elicit knowledge from the experts. The aim here is to see the world from the point of view of the informant, become immersed in their detail and get close to the phenomena of interest (Johnson & Harris, 2002). It was apparent that this was a rich data source to include observations and words for which an effective research design was required to successfully demonstrate the aim and objectives set out in section 3.1. There are choices to be made regarding the design of research. There are several approaches to the research task according to the purpose of the research. Furthermore there are different strategies for carrying out research. These are explored in the following sections with justifications for why a particular stance has been taken by the author.

The nature and extent of cutting tool design knowledge has not been investigated. The research problem highlighted that it is currently unknown how the knowledge within the domain interacts, what is the structure and how the designers use this knowledge to design the product. According to Robson (2002) the purpose of the research enquiry can be: exploratory, descriptive, or explanatory. The purpose of this research can be described as a need to explore cutting tool design with the emphasis on the capture and reuse of this knowledge. Exploratory research entails the researcher to find out what is happening, to seek new insights and to ask questions in order to develop new ideas and hypotheses for future research (Robson, 2002). The purpose of the research affects that 'type of research' or 'research approach' that is undertaken: this can be quantitative or qualitative which is addressed in the next section.

3.2.1 Type of research carried out

Deciding upon a suitable strategy for a piece of research invariably requires that the researcher considers the type of research that can be undertaken as this will influence the type of data collected. In most research cases there lies an opportunity to focus the study towards either qualitative (flexible) or quantitative (fixed) design. These can be summarised as follows:

> ***Quantitative design*** Characterised by the analytical approach to the data that are generated and always involves the numerical analysis of data (Johnson & Harris, 2002). It calls for a tight pre-specification before

the main data collection stage; hence the term fixed design (Robson, 2002).

Qualitative design The data are collected in the form of words and observations, as opposed to numbers and the analysis is based on the interpretations of these data as opposed to statistical manipulation (Johnson & Harris, 2002). Qualitative design is associated with research questions and phenomena of interest that requires an exploration of detailed in-depth data, aimed at description, comparison or prescription. The design often evolves during the data collection; hence the term 'flexible' design (Robson, 2002).

It is not possible to undertake both qualitative and quantitative research together, but it is possible to have phases of the research that can take a qualitative approach followed by a quantitative approach and so on. However, being a 'real-life' problem (that is one that requires the interaction of the author with people in the cutting tool industry on a day to day basis) suggests a methodology that interacts with people and generates data that is non-numerical or in the form words and observations, therefore the selected research type is 'qualitative'. Typically, the knowledge elicited by the author from the cutting tool designer is going to be of 'how?' or 'why?' type of questions relating to the solving of design problems. In these instances the designer will provide answers that are from experience which are given by describing the solution to the author in the form of words or observations.

Understanding that one needs a qualitative approach to the research problem gives us an indication of how to perform the research i.e. what strategy we are going to assume. The next section provides an overview of the main research strategies associated with a qualitative research approach: case studies, ethnographic studies and grounded theory studies.

3.2.2 Research Strategy

In flexible (qualitative) research, several strategies or design traditions can be employed to investigate the problem and provide a framework for the research. Table 3.1 illustrates the main strategies involved in qualitative research design. For this research problem it is possible that any of the three research strategies in table 3.1 would suffice as a strategy for solving the problem stated in chapter one. The strategies present different ways of collecting and analysing the data obtained. However, in line with the recommendations of the EngD programme, the collaborating organisation is to be treated as a case study. In line with this recommendation it is proposed that a case study based strategy is used within this research. With the observations of the initial one-month period in the organisation it was highlighted that the ideas and theories about cutting tool design would emerge as the author participate further in the design process. Also the work carried out in the initial one-month period with the sponsoring organisation were undertaken as several small individual cutting tool design cases and hence the selection of a case-based research strategy. According to Gummesson (2000) the case study approach is becoming increasingly widespread in management.

Table 3.1: Main strategies in qualitative research design (Robson, 2002).

Case Study	Selection of a single case (or a small number of related cases) of a situation, individual or group of interest or concern; Study of the case in its context; Collection of information via a range of data collection techniques including observation, interview and documentary analysis.
Ethnographic Study	Selection of a group, organisation or community of interest or concern; Immersion of the researcher in that setting; Use of participant observation.
Grounded Theory Study	Applicable to a wide variety of phenomena; Commonly interview based; A systematic but flexible research strategy, which provides detailed prescriptions for data analysis.

A case study based research strategy focuses on understanding the dynamics present within single settings (Huberman & Miles, 2002). Two types of case study emerge: the first attempts to derive general conclusions from a limited number of cases and, the second attempts to arrive at specific conclusions to a single case (Gummesson, 2000). Adopting a case-based research strategy combines the use of several data collection techniques such as observations, interviews, and documents. Undertaking a case study raises a number of issues (interpretation, bias, validity) regarding rigour in the use of the case study approach. The next section addresses these techniques and issues.

3.2.3 Data collection techniques

Case studies typically combine data collection methods such as interviews, questionnaires and observations (Huberman & Miles, 2002). All three data collection methods aforementioned have been utilised during the research programme. Interviews have used to highlight the views of cutting tool designer's at the sponsoring organisation and at industry competitors. The author has used participant observation to examine the nature and extent of the cutting tool design process to develop the ontological framework and the viewpoint of design reuse. Questionnaires have been used in the validation and testing phases of the theory built in chapters six & seven of this research to obtain the opinions of the experts within cutting tool design in their assessment of the theory generated within the research. At each of these stages there is a question of validity of the results of using the research approach. The next section highlights the main threats to validity describing how the author has overcome these threats.

3.2.4 Validity

The main threats to validity in flexible research are interpretation, reactivity, respondent bias and researcher biases (Robson, 2002). Interpretative validity measures whether the account given is that of the participants rather than based on the researchers perspective and categories. Reactivity refers to the way in the researcher's presence may interfere with the case setting. Respondent bias refers to the instances where the respondent may withhold information or tell the researcher what they think the researcher wants to know. Researcher bias refers to what preconceptions and assumptions the researcher brings to the situation.

3.2.5 Reducing the threat of bias within the interpretations

The qualitative approach to research requires a level of interpretation in the events that the author is participating or observing. Reducing these biases required the author to:

- Prolong his involvement in the design process and therefore ensure that respondent bias and reactivity were reduced. As the author became accepted into the design process and the initial reactivity reduced by the author becoming aware of the issue in the design process. The development of a trusting relationship ensued thus reducing the threat of bias information being given.
- Triangulate his experience of the domain by using different methods of data collection including observation, documents and interviews. Also the author the used both a qualitative and quantitative method in the testing and validation of the theory developed.
- Keep an audit trial of the observations, activities and designs undertaken so that the researcher bias was reduced.
- Developed relationships with more than one expert i.e. several sources of data in the design process to enable the "member checking" in the interactions that were taking place.

Based on the above analysis the methodology for the research is described in section 3.4. The next section describes the scope of the research.

3.3 THE SCOPE OF THE RESEARCH

The extent of the research is to elicit, formalise and reuse the knowledge required in the special purpose cutting tool design process. Special purpose cutting tool design produces either a "one-off" cutting tool or a set of cutting tools in which the design solution cannot be satisfied by the use of standard "off-the-shelf" tooling. The task of cutting tool design is a knowledge intensive activity requiring several years of experience to be done effectively.

The proposal stage being the value added activity of the design process is initiated by a salesperson visiting a customer and taking an initial look at the perceived problem. It is the sales engineer's job is to understand what the customer perceives as a problem. He/she then transfers this perception in terms of goals and constraints to the proposal form as shown in figure 3.1. Thus the purpose here is to elicit information from the customer and interpret this to provide a proposal for the designer. In many cases the salesperson may even suggest a solution and supply the completed form, without any component drawings and/or existing tooling specifications. The decisions considered here are deciding what can be designed and will provide a workable technical solution. Further trends in the industry are moving to the customer requiring a complete tooling solution rather than the previous "one-off" cutting tool. This adds to the complexity that the salesperson faces when assessing the customer requirements.

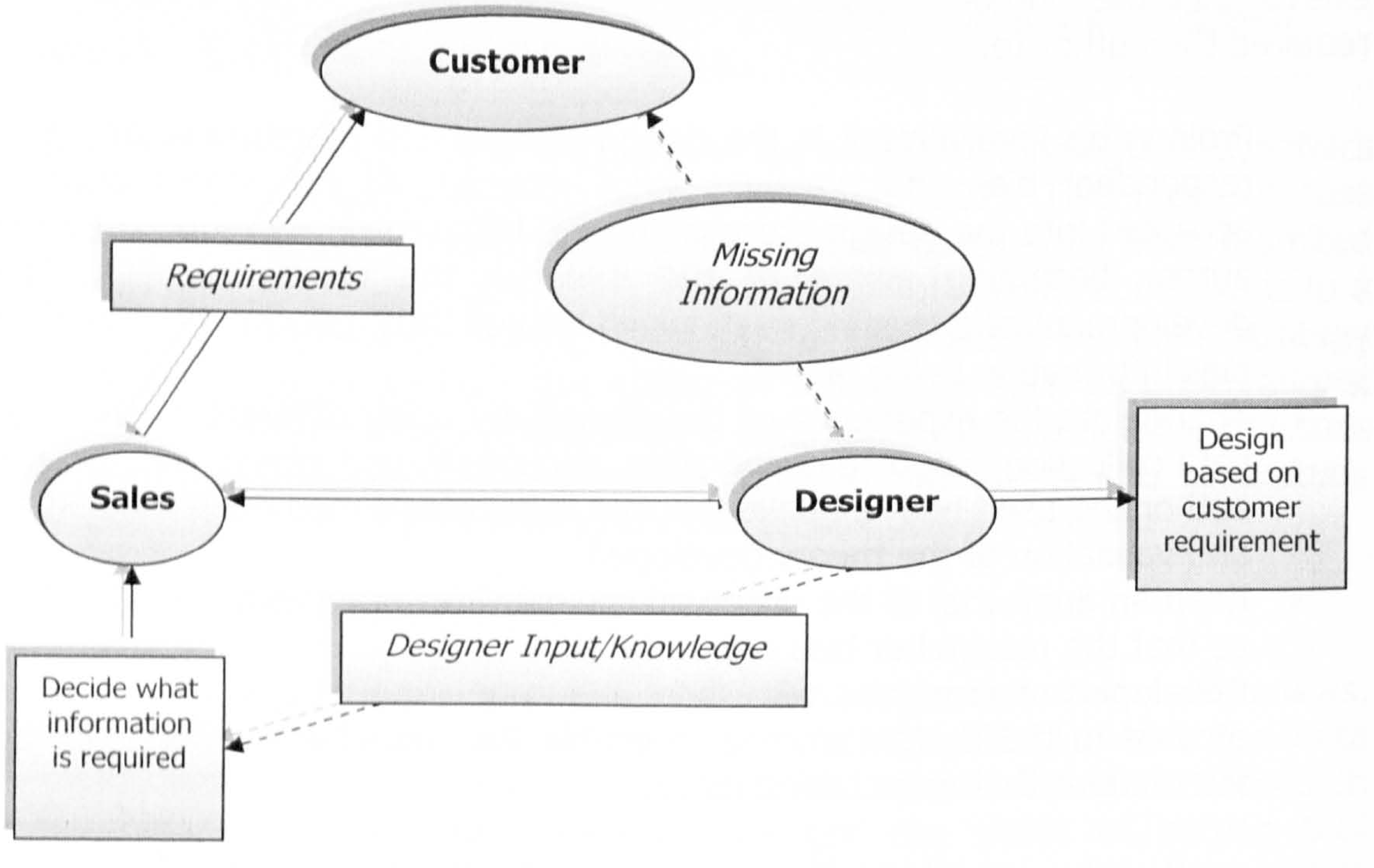

Figure 3.1: The AS-IS cutting tool design process (Bailey & Roy, 2002).

When a proposal comes into the department, the expert screens the proposal. He/she will look at all the documents provided and in most cases produce a 'layout' in which he will draw out the component and a tool, which he thinks will do the job. It takes the expert approximately 4hrs to assess a proposal and produce a concept, with the quickest being only twenty minutes and some taking 2 days. The decisions made concern the appropriate selection of components to satisfy the proposal. For example, the designer will decide what *style of insert* is required for the problem and will also recall previous designs and decide upon the closest match to the current problem based on the insert selection.

It is proposed in this study that special cutting tool design is studied in general to gain an understanding of the nature and extent of the domain. The types of cutting tool encountered have been those major categories of tools in the automotive and manufacturing industries: these are milling, turning and drilling. The types of product are presented in figure 3.2. This will be followed by a focused investigation into the designer/salesman interface to provide a more detailed level of the knowledge required for special cutting tool design. The study will capture the knowledge requirements from the interaction of the author and the design experts within an industrial environment.

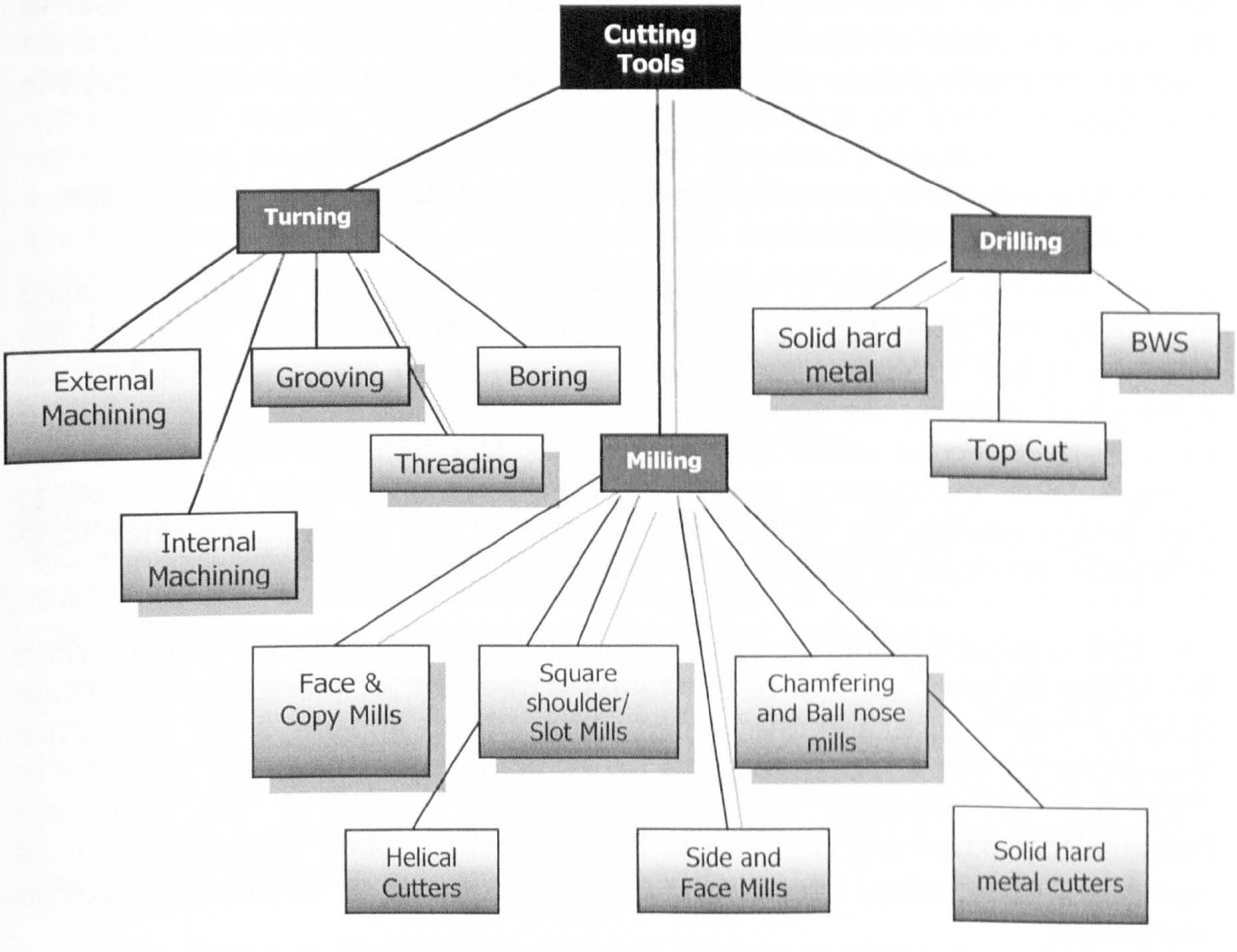

Figure 3.2: Examples of encountered cutting tools during participation.

3.4 RESEARCH METHODOLOGY

It is the philosophy of the Engineering Doctorate (EngD) programme that the research project must address an industrial based problem that is significant to that industry. The requirement for the EngD is to include a collaborating organisation, and for the student to interact closely with the organisation. The EngD programme requires the research engineer to approach an industrial based or 'real-life' problem with a viable research methodology to meet the needs of a doctoral thesis. It is recommended that the collaborating organisation be treated as a case study.

3.4.1 The capture & reuse of design knowledge

The purpose of the literature review is to develop an understanding of the field of interest: indicating the most important issues and relevance to the capture and reuse of cutting tool design knowledge. Investigating how the various knowledge engineering techniques can aid the design process and the capture of design knowledge. This includes the techniques of knowledge modelling to aid the elicitation, acquisition and capture of design knowledge. The use of Case-Based reasoning (CBR) techniques aiding the engineering design process for the selection of an appropriate CBR technique can be used as a tool to facilitate the reuse of cutting tool designs. This would give a state-of the-art view of the existing theory: identifying strengths, weaknesses and the gaps in this theory.

3.4.2 Knowledge = Expert – Novice (KEN): A novel methodology for Knowledge Elicitation

As the literature review in chapter two has highlighted a gap in existing knowledge elicitation techniques relying on the interviewing of expert as the main technique to elicit design knowledge. In many industries including the cutting tool industry, the apprenticeship is seen as a necessary route to gaining the expertise needed within the domain. This fact combined together with the author's initial participation (used as a familiarisation exercise) in the cutting tool design domain led to the development of the participatory knowledge elicitation technique of Knowledge = Expert – Novice or KEN.

The KEN approach requires a novice to undertake the task of the expert. When the novice becomes stuck or begins to make mistakes an interaction takes place between the novice and the expert. The expert imparts some of his/her knowledge to the novice through a series of questions asked by the novice. Thus the KEN approach provides a structured account of this interaction between the expert and the novice. The method combines techniques such as participant observation, interviewing and protocol analysis to collect the design knowledge.

The approach was validated through several pilot studies by the author and Cranfield University researchers to examine the effectiveness of KEN to capture knowledge with the author being a non-participant observer. In the first study, KEN was used by the author in a typical cutting tool design environment. In the second study another Cranfield University researcher used KEN to capture cost estimating knowledge and in the final study, KEN was used to interact with a cutting tool expert to elicit a set of design descriptor terms. KEN was then used by the author to examine the nature and extent of cutting tool design knowledge in chapter four and subsequently in chapter five.

The results of the KEN process by the author were to suggest that the nature and extent of the knowledge in cutting tool design was a combination of internal, external and technological knowledge. Each of these knowledge types could consist of implicit, explicit and heuristic knowledge types. Furthermore, it was highlighted through this technique that the key value added stage within the design process was that of the proposal stage, and this was further investigated to highlight a more detailed level of the types of knowledge required in cutting tool design.

3.4.3 Knowledge requirements for special purpose cutting tool design

KEN has identified the sales/designer interface as the key value added task through the participation of the author within the design process. By participating and observation in the process the author identified several instances of missing information from the provision of information to the designer from the salesperson in the process described in section 3.1. It is quite natural to ask a question when the answer is not known; the reply often yields the knowledge to solve the problem or design. A matrix approach to determine the knowledge requirements of the cutting tool designer was developed from the background and understanding developed by the author and existing works in the literature. Also the author visited two further cutting tool industry competitors to further his understanding of the nature and extent of design knowledge used within the cutting tool design industry.

Fifty proposal forms were selected at random from the design files at the sponsoring organisation. These are categorised by the author according to the level of complexity that the author perceived each to correspond too. Based on this classification two salespersons (interviewed individually) were asked to assess the level of perceived design involvement that they considered the designers would undertake upon receipt of each of the fifty proposal forms. After interviewing the two salespersons the author selected two designers, one expert and one novice. They were asked to identify the knowledge required that was not supplied within the proposal documentation i.e. the problems that the designer faced with supplied proposal form.

From the literature review it is observed that to compare two different but related variables together, a matrix shows the interactions of the variables visually. The salespersons view is to anticipate the design lead-time i.e. when the product arrives at the customer's site. The designer view of the proposal stage is to analyse the proposal form and overcome any problems faced with the information given. The author linked these two views by understanding the design process at the collaborating organisation and considered the types of design undertaken and the activities in the design process shown in figure 3.3.

The two matrices were then developed as an information collection technique by the author to examine the interaction between 'types of design' and 'design activities' and the design problems. The approach requires both expert and novice participation in the process to verify that the information obtained is appropriate to the design process. The next section describes the development of an ontology-based framework for cutting tool design knowledge representation.

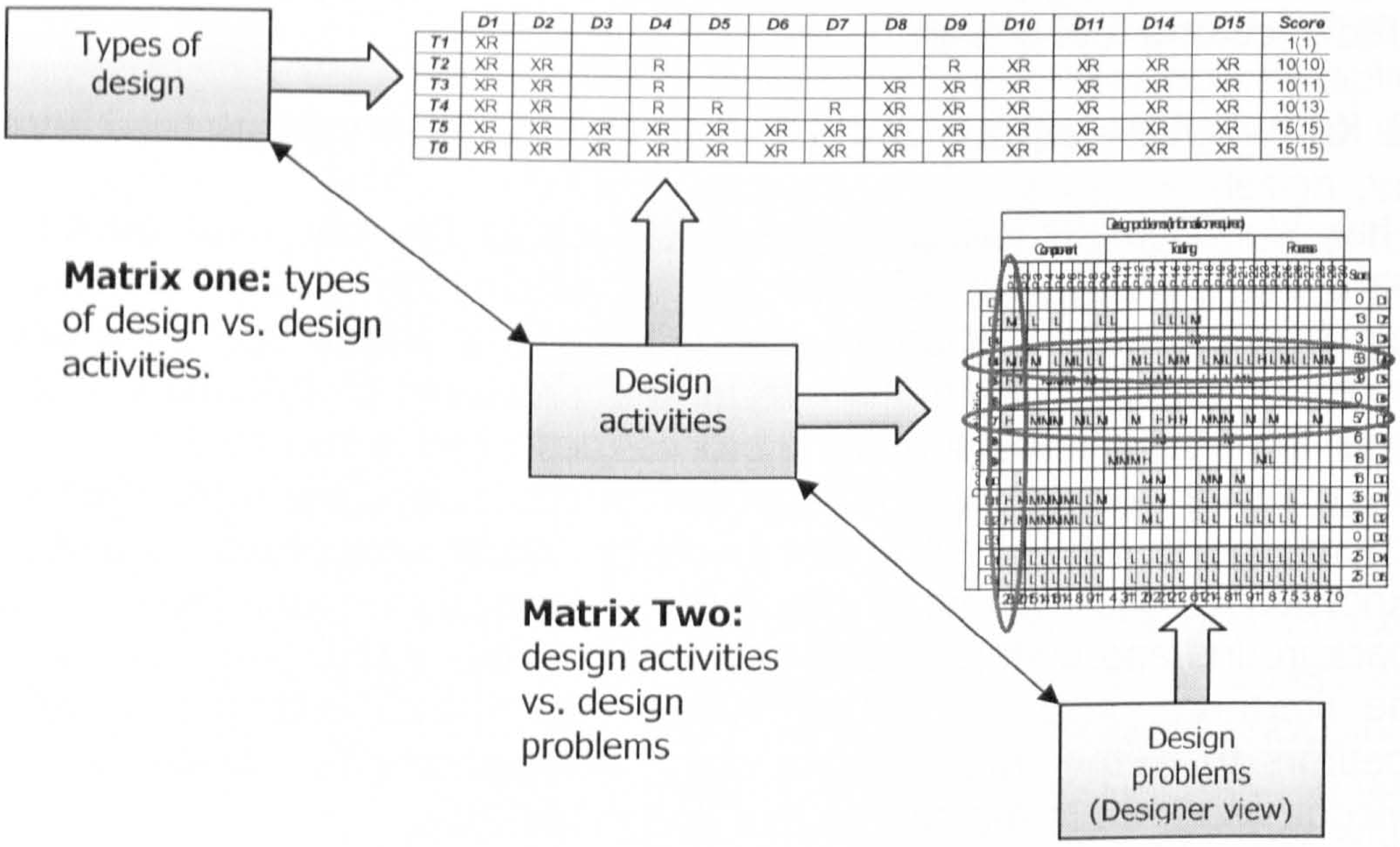

Figure 3.3: The matrix approach.

3.4.4 Developing an ontology-based framework for cutting tool design knowledge representation

In order to gain a deeper understanding of the cutting tool design domain a functional ontology, behavioural ontology and a structural ontology were developed. These ontologies describe the concepts of the domain and relationships amongst these concepts. The concepts were derived from the expert and novice opinion during a workshop carried out by the author, and an existing literature and video lecture series on cutting tool design. A decomposition of each of the three ontological commitments was undertaken viewing the cutting tool and work-piece as a complete system where the each of the individual components experiences a change of state. For example, the work-piece will undergo a change from the initial raw material to a finished product. For each concept identified a further decomposition was undertaken. The Function-Behaviour-Structure (FBS) approach was adopted, as it is common for designers to work with the functions of a component when they are designing a product. In a reuse situation a past design is selected based on the functional similarity that it exhibits with the proposed design. The aim was to identify which detailed knowledge terms were related to the functional decompositions undertaken above. However, it was seen that some refinement was required, as there were some inconsistencies with the interpretation of function, behaviour, and structure. An iterative procedure produced a final functional ontology.

Three design experts within the cutting tool domain validated this final ontology in a paper-based form for completeness. The first stage of the validation was to examine and assess the terms identified in the functional ontology and rated each term based on a questionnaire. In the second part of the validation three design cases (a proposal form, component drawing and final design) were selected from the original 50 proposal selected in section 3.2. These designs were presented in tabular form. The first column in each table (one for each case) described the part of the functional ontology instantiated. The second column presented the information extracted from the design case. The third column provided a description of the information presented in the 2nd column. The three experts were required to examine the tables and cross-check the knowledge populated in tabular form. After examining each case the experts were requested to complete questionnaire on the completeness of the cases.

It has been recognised by the author that this ontology incorporates the whole view of special cutting tool design, which would be too detailed for implementation onto an application platform. It was required that a reuse viewpoint to access the design drawings be taken from the ontology for the application required. The next section describes the approach taken to derive a viewpoint from the ontology for effective reuse.

3.4.5 Implementing a viewpoint of design reuse

The ontology development above provided a basis for the development of a reuse application. A reuse viewpoint of the ontology was taken and then mapped to selected Case-Based Reasoning (CBR) software. The purpose of the viewpoint was to provide a method of design retrieval by both salespersons and designers at the preliminary stage of the design process. The viewpoint was selected by user requirements identified through interviews with experts at Widia Valenite, Kennametal Hertel Ltd, Sandvik UK, and further research carried out at Cranfield University in conjunction with this research. Designers at Widia Valenite were asked to select the terms, which they would use to search for a design. These descriptors were mapped to the ontology and the appropriate viewpoint of the ontology was implemented within CBR software. The free CBR software was selected for its ease of use (it didn't require a vast amount of learning to use it), the popularity of the software in the research community and the number of successful industrial applications that have developed using the software.

Ordered hierarchy for cutting tool applications mapped the viewpoint for reuse onto the CBR shell. Additionally, several sub concepts were added to store the hard facts about the applications obtained through the descriptors mapping of the ontology. The setting of the attributes and the values that they can hold followed this sub concept definition.

This model was validated in the MSc research conducted in conjunction with this research. In this case, the researcher considered a novice within the cutting tool industry, carried out an initial pilot study for which design problems he was familiar with, and then with a set of five design problems that he had never seen before.

The author of this research validated the CBR tool with experts at Widia Valenite (two salespersons and five designers). Five design cases were selected to test the CBR tool. Two of the cases were represented by designs in the case base and a further three were chosen that did not have a design residing on the case base. The purpose here is to use the documentation to identify terms from the cases for the descriptor terms and extract them to search for the designs within the case base. The former two cases were used to check that the case base was returning the correct cases and to allow the participants to familiarise themselves with the system. The latter three cases were used to demonstrate the similarity of cases obtained. Both sets of users in this case are validating for usability and the effectiveness of the system to retrieve a design. The user responses are captured by a questionnaire and tape recording and then transcribed to identify the success of the measurement criteria i.e. the user requirements.

3.5 SUMMARY AND KEY OBSERVATIONS

This chapter has described the aim, objectives, and scope of the research work. It highlights the methodology that has formed the basis for the work carried out in this research including literature review, the development of a method to capture design knowledge by novice participation, the capture of detailed level knowledge at the proposal stage, the development of a special cutting tool design ontology and then describes the implementation of a viewpoint of the ontology onto an appropriate CBR shell.

It has been highlighted that there is a gap in current knowledge elicitation techniques, which have a limitation in that just ask the expert to part with his knowledge. In this chapter a method to elicit knowledge, Knowledge = Expert – Novice (KEN) has been described and that using this method the novice can gain expert knowledge and identify key value added tasks within the design process has been emphasised. From the high-level view of the knowledge obtained using KEN, a matrix approach has been proposed and described to capture the detailed level knowledge that is required in cutting tool design. This has prompted the development of a special cutting tool design ontology based upon a functional ontology, a behavioural ontology and a structural ontology. It has been suggested that an implementation of this ontology depends on the viewpoint that is taken. In this case the implementation is based from the viewpoint of design reuse and that a set of descriptor terms have been derived that allows the selection of the viewpoint from the overall ontology. The viewpoint is implemented onto CBR software as discussed.

The next chapter now describes the development of Knowledge = Expert – Novice (KEN) to identify the key value added task in special cutting tool design.

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CHAPTER FOUR

Knowledge = Expert – Novice (KEN): A novel methodology for Knowledge Elicitation

4.0 INTRODUCTION

It has been highlighted that the elicitation of expertise (knowledge) within a design domain is difficult to achieve in an industrial situation without active participation in the design process. Also, the trend in the cutting tool industry with the loss of expertise through demographic changes has led the industry to recruit new designers to the industry by providing apprenticeships. The benefits of 'on-the-job' learning are thought to be of benefit for passing on of expertise within the industry. Therefore, using a novice to participate in the design process would provide a richer picture of the expertise within cutting tool design.

This chapter highlights the participation of a novice in the design process to explore the nature and extent of knowledge in cutting tool design. The author (novice) spent six months within the organisation. During this time he interacted as a member of the organisation designing special cutting tools for external customers. The tasks undertaken were typical to the cutting tool industry and would be those that an expert would undertake. It was realised that the novice found he was stuck or having difficulties with the design task through lack of knowledge, which inhibited him finding a solution. This required an interaction with the expert/s to enable the novice to solve the problems he faced. The Knowledge = Expert – Novice (KEN) framework was borne through these interactions between the novice and the expert. The novice describes the problems he faces and produces a set of questions that he can ask the expert. The expert responds with solutions to the problems found by the novice and hence imparts some knowledge of the domain to the novice.

In section 4.1 the industry view of the nature and extent of design knowledge is given with the discussions at two further cutting tool industry organisations. Section 4.2 provides the reasons for a methodology to capture design knowledge and provides criteria to assess its success. The development of the KEN methodology is discussed, followed by the description of the KEN methodology in section 4.3. This is followed by the application of the methodology in a number of examples of using the KEN process in an industrial context in section 4.4. Section 4.5 evaluates the KEN methodology against the criteria set out in 4.2 and compares its strengths and weaknesses against other knowledge techniques. Finally the chapter is concluded in section 4.6.

4.1 INDUSTRY VIEW ON THE NATURE AND EXTENT OF DESIGN KNOWLEDGE

As described in chapter one, there are several large organisations in the cutting tool industry within the UK. It was apparent from the initial work carried out by the author through the MBA programme that Widia Valenite operated in a mature market where expertise in the design and sales functions led the cutting tool development cycle. This view was further confirmed with the author participating within the cutting tool environment at Widia Valenite. To understand this expertise; the author was required to examine the nature and extent of the knowledge within the design process not only at Widia Valenite but also within the cutting tool industry. This section describes the views on the nature and extent of the knowledge within cutting tool design from personnel at Kennametal Hertel UK, Sandvik Coromant UK and Widia Valenite UK. The views were collated by interview and visits to the individual company sites. The purpose is to arrive at a generic view of the nature and extent of knowledge in cutting tool design. This view was then used to examine with more depth the nature and extent to the knowledge within cutting tool design at Widia Valenite UK.

4.1.1 Participant organisations

Kennametal Hertel UK designs specials for both the UK and some of their sister companies in Europe. Design offices, include a small one in France and a large one in Germany - the European headquarters, and there is large corporate design office in the United States, Latrobe where standard products are designed. *Sandvik Coromant UK* has a head office in Sweden plus manufacturing sites throughout the world. Halesowen is the site for UK specials design, manufacturing and sales. Sandvik is a large company, which produces cutting tools, its own tubing and software. *Widia Valenite UK* is based in Milton Keynes, which is a small site (35 employees) specialising in the design of specials for the UK market. Its parent company is based in Germany.

4.1.2 Interview design

A questionnaire was designed so that the interview remained semi structured so that the interviewer could cover the range of interests but still allow the exploration of avenues that were being sought by the interviewee. One interview was carried out at Sandvik with three individuals. At Kennametal, an interview was carried out with the production manager for the site, together with a tour of the facilities and time was allowed for discussions with the designers.

Analysis of interviews

During the interviews the author took written notes together with audiotape recording of the discussions that took place based on the questionnaire. The audiotape was later transcribed. For each question the author looked for the terms that were of interest to this research. These terms include knowledge capture, knowledge reuse, design processes, opinion on the terms knowledge and experiences of the participants in the study. The responses were grouped according to the four sections mentioned below.

Interview question structure

The structure of the interview questionnaire was in several sections. A sample questionnaire is given in section A1 of appendix A.

Section one asked questions relating to the design process: to find out about the process itself, the people involved and the steps taken in the design process. Specific questions relating to the actual design process they use in their specials design i.e. the organisation of the design activity and reuse of previous designs in this design activity. The purpose here was to identify the major features of the design process, which relate to the research topic.

Section two aimed to highlight the level of customer interaction that was used during the design process. Customer interaction and support is another important aspect emerging in today's industry and it is felt by the author that customer knowledge is an important factor when capturing knowledge about the design process. This can include customers' requirements, cost factors and problems occurring with tooling supplied. Therefore this knowledge can be used in conjunction with future designs so that the same problems are not repeated. It was felt necessary to identify the levels of customer interaction and support given by each of the interviewed companies, and the kind of feedback that was given to the design teams and how the knowledge was utilised.

Section three asked of their opinion on the levels of experience required to design a cutting tool. Within the design office at Widia Valenite the long serving designers are all from apprenticeship backgrounds, and there are two members who are currently on apprenticeships. The apprenticeships provide design experience in the design office and this is supplemented up by a hands-on metal cutting experience through local colleges. In an industry that is heavily knowledge intensive it is important to understand the routes that can be taken to become a designer. The companies interviewed had their own preferred methods of recruitment of individuals into the design business. Furthermore, it would be interesting to find out how these companies pass on the design knowledge possessed by their experts to these new recruits.

Finally, section four explored each organisation's use and awareness of knowledge based tools including expert systems. The reuse of past designs is a factor in this research, and the interviews were used to find out whether each of these companies is practicing such activities. Relating to the issue of knowledge capture within the organisation, and to its extent, if there were such practices could they give examples. Also what level of knowledge management is the company embracing?

4.1.3 Design processes within the industry

The design activity is organised very similarly at both Sandvik and Kennametal; first they have a team who prepare the proposal and quotation, which is then passed on to the CAD designers who transform it into a workable design. Design lead times vary from around 4 weeks for Kennametal (the design time can be 4 hours from concept to finished design depending on the complexity of the cutting tool), which is similar for Sandvik (their design time is one day to one week again depending on the complexity of the cutting tool). Sandvik have 26 designers based on two sites in the UK, whereas Kennametal have five CAD designers together with a number of applications engineers who prepare the proposal and quotations. Widia Valenite is a smaller outfit, four expert designers and one apprentice designer. The chief engineer (one of the experts) scans the proposals submitted to the design department and then the designs are detailed by the other experts and also by the chief engineer. The design time varies again on the complexity from 2 hours to 4 days.

4.1.4 Customer interaction

Many of the principles for a design come from the customer. Customers in this country are quite demanding, a lot of them know what they want or they think they know what they want. They make a lot of specifications of what they want the tool to be like, for instance, what type of inserts, what type of cutting angle, so really the customer will put constraints on the design he wants to buy. It is very rare that you get a clean sheet of paper to do a design, the constraints of size of machine, capacity of machine.

Designers require sales-led information relating to customer capabilities. This may include costs that the customer is willing to pay, delivery times and methods and what the customer prefers in terms of tooling. There are a range of customer types; some customers that will take the best and most advanced tooling available, but others that will only take on the most simplest of boring bars. However, the customer is the king and they know their parts as they have the product knowledge being the end-users. A critical area for cutting tool knowledge is how the product performs in the market place. There are two types of customer, one who is confident of what they want and the other who will have problems regarding the tooling that they require.

The design activity is split into two parts; the first part handles enquiries from the customer (the customer sends in information about a certain operation he wants to perform then we come up with some design or proposal and a quotation); and the second, order comes in and they prepare all the information and the data processing to actually manufacture the tool. There are various ways of getting information from the customer, directly or via salesmen.

Sales engineers have various forms they can fill in for type of tool or what it needs to do or what it is capable of. This is sent directly to the designer who will interpret the information.

4.1.5 Use of experience

At Widia Valenite the new recruits are trained by actually designing cutting tools, simple single point tools at first before moving on to more complex tooling under the guidance of an expert. This is mirrored in the other two organisations. In terms of recruiting new designers all three companies tend to prefer to bring people through an apprenticeship scheme, where the recruits learn metal cutting skills for a minimum of four years. The individuals can then move into positions in the design teams as design apprentices learning through a 'piggy back' system. The apprentice will sit with the expert designer and learn through design examples. It has been noticed by these companies that there is a void or gap in which quality engineers are just not being found to fill the positions they have and thus have taken it upon themselves to provide suitable training of their own which is best for the company. Three to four years is the minimum level of experience for a person to be considered safe to handle design work. There are specialists in particular areas of cutting tool design, for example, Kennametal have two specialists in the design of milling cutters which are significantly more knowledge intensive then single point turning tools. Sandvik do have experienced designers who will concentrate on particular cutting applications but there have been instances when individuals have moved to different areas of the design office.

4.1.6 Knowledge capture & reuse

There is no real effort to capture rationale on design decisions at any of the three companies on specials design as the time frames for design doesn't allow for this rationale capture. However, certainly in Kennametal's case they would expect to retain why certain decisions were taken when designing standard tooling. For instance while performing value analyses on standard products they would expect to see why particular cost decisions were taken to be recorded on the design model. Both companies see its value but until this type of technology becomes more user friendly in terms of the bottlenecks i.e. inputting data into the system so that a previous design can be found that similarly matches current requirements. Currently, Kennametal are working on a design register which enable them to input certain parameters and then give the closest existing design which can be modified but this system suffers the same technical problems as above.

The person interviewed at Kennametal, who is in charge of the engineering function for Kennametal in the UK, is aware of a particular expert system that they use on a regular basis, called the TESS system. If a feature (with other information) to be designed is described to the system, the system will come up with a solution. It uses a database of some 15,000 existing design models. This system provides users with the facility to enter parameter values (e.g. insert size) of the cutting tool and the system creates a design based on those parameters which include the tool holder. However, this system is limited to standard tooling.

Reuse of past specials design within the industry is common practice. Widia Valenite from the observations and participation in the design process certainly make use of past design cases. Both Sandvik and Kennametal confirm this: "...where possible if you've done it before, you don't want to do it again". They are always looking for a tool that has been used before on a new problem.

4.1.7 Summary

The scale of the design functions in Kennametal and Sandvik are larger than that of Widia Valenite in the UK. However, the knowledge requirements are similar for all three organisations. In fact the challenges for each organisation (referring to chapter one which highlighted the state of the cutting tool industry in the UK) are the demographic changes within the industry. It can be seen that the preferred route to becoming a designer within the cutting tool design is through an apprenticeship, requiring several years of experience to be considered an expert in cutting tool design.

The challenge is to pass on this knowledge of the experts in a way that is natural to the industry – i.e. apprenticeships, 'on-the-job' training or learning. This means teaching the knowledge in the design process, commercial aspects of the design process and the technical knowledge that is required for success within the industry. According to this view within the industry, the next section discusses the requirement for methodology for the capture of design knowledge.

4.2 REQUIREMENTS FOR A METHODOLOGY TO CAPTURE DESIGN KNOWLEDGE

Chapter two has highlighted the major methods for knowledge elicitation. It has been observed by the author that many of these lack the characteristics necessary for the design task and hence can be improved. The nature of the design activity relies on experience of the designer. In order to gain experience of the domain one has to participate in the day-to-day design tasks. This view has been echoed by the cutting tool design industry in which novice designers experience a period of time with an expert designer or "sitting with Nelly" before being allowed to undertake designs themselves. However there is a lack of methodologies to elicit knowledge based a novice participating in the design task.

The requirement in this thesis is for a knowledge elicitation methodology that allows the author to participate in the design process. Participating in the design tasks carried out on a day-to-day basis requires a structured approach. In this case it is the difference between the expert and novice that defines the task knowledge that is elicited: Knowledge = Expert – Novice (KEN). Existing knowledge elicitation techniques fail to address the need for a novice designer to experience hands-on design. Rather these are limited to observations of expert designers but only small problems that can be dealt with in a short space of time during an interview or observing a protocol analysis.

Therefore the requirements for task knowledge elicitation for have been discussed in several formal and informal meetings with the sponsoring organisation designers, salespersons and management staff. Also to obtain an industry view of the nature and extent of design knowledge designers and sales staff at industry competitors were also formally interviewed as described in section 4.1. This has lead to the derivation of the following requirements:

- A structured approach that shows the interactions between the expert and novice;
- A record of the these interactions in the form of a template or similar;
- An identification of key task information and knowledge;
- The novice learns form these interactions;
- A generic approach that can be applied in other task-based activities.

Then next section describes the development of the KEN methodology.

4.3 DEVELOPMENT OF KNOWLEDGE = EXPERT – NOVICE (KEN) METHODOLOGY

Achieving a richer understanding of the nature of the design problem requires active participation in the design process. By active participation, the knowledge elicitor is required to perform the actual design tasks as carried out by the expert. Most current knowledge elicitation methodologies just ask, observe (or both) the expert do his/her task and do not allow the novice to participate in the design process. In 'on-the-job' learning the novice is required to interact with a domain expert and learn the tasks of the domain. In a similar fashion a novice is placed in the design process and, by asking questions to the expert when experiencing difficulties knowledge of how to perform the tasks should arise.

The author (novice) spent a total of seven months (an initial one month, followed by a six month period) with the collaborator to identify the nature and extent of knowledge in cutting tool design. This provided the author a chance to interact with the domain experts on a daily basis and understand at first hand the processes undertaken by the experts. A participant observation approach was taken to allow the author to become accepted in the organisation, so the process did not threaten the experts. Furthermore, due to the dynamic nature of the environment the availability of the expert is at a premium but due to the author being part of group and undertaking design projects of his own the interaction was natural. This is because the work undertaken by the author was for customer orders and required the experts to give the appropriate knowledge for the designs to be a success. As with any participant observation study; a detailed account of the tasks undertaken and observations were recorded. However, many of the discussions and interactions with the experts were often informal discussions where the experts were most at ease with imparting his/her knowledge to the author.

4.3.1 Motivation to develop KEN

Design is a knowledge intensive task. However capturing all knowledge is not an option. Knowledge is defined as Knowledge = Expert – Novice and can be seen to be the difference between the expert and the novice. To establish the difference between the expert and the novice at knowledge level a structured methodology called K = E – N is developed. KEN requires a novice to participate in the working environment and perform tasks as of an Expert. The knowledge capture methodology also allows the Novice to learn a domain, similar to an apprentice.

The author designed several cutting tools over a period of 6 months within the organisation. These ranged from single point turning tools to more complex milling tools. It illustrated the difference between the novice designer (the author), and an expert, who has around 28 years experience designing cutting tools. During the design training and observation case studies it was possible to identify knowledge of cutting tool design through interaction between the novice and the expert designer. These interactions occurred as a result of the novice experiencing the following behavioural manifestations or barriers to learning:

- Being stuck or experiencing difficulties;
- Having a correct solution but not an optimised solution;
- Having an incorrect design;

The experience of the design process highlighted that these behaviours were taking place. Using participant observation as a research strategy allowed rich knowledge to be acquired; the KEN process was seen to come out of these interactions. In order to show its suitability as a generic tool for other domains, an example from the cost-estimating domain is presented. The nature of the domain in which the KEN methodology can be applied, is in domains with knowledge intensive tasks that have applicability to apprentice- or shadow-type learning situations. This situation requires that the novice can undertake similar tasks of the expert.

4.3.2 Level of knowledge obtained

The level of knowledge obtained is driven by the level and context of the design task undertaken by the novice. If a simple example is given then the knowledge gained will be shallow but as the complexity of the design task is increased then the knowledge gained will be deeper. The context of the work is also an important factor in the knowledge obtained by the novice. For example, as is the case with the examples shown later in this chapter: the work carried out was for actual customers, and as such required both the experts and novice to take the task seriously for potential revenue to the organisation. However, undertaking tasks that were artificial (made for the purpose) would not bring the same amount of responsibility to the KEN process.

4.3.3 Novices and experts

Within the cutting tool industry three levels of participation have been observed in design: novice, apprentice and expert. For the purpose of this research they are defined as follows from Hoffman (1998):

- ***Novice*** – A person who is new, a probationary member, who has had some 'minimal exposure' to the domain but requires further assistance from the expert to perform design tasks.
- ***Apprentice*** – One who is learning – a student undergoing a programme of instruction beyond the introductory level. The apprentice is immersed in the domain.
- ***Expert*** – Highly regarded by peers, whose judgements are uncommonly accurate and reliable, whose performance shows consummate skill and economy of effort, and who can deal effectively with types of rare or 'tough' cases. Also an expert is one who has special skills or knowledge derived from extensive experience with sub-domains.

Expertise in any domain consists of knowledge and skill (Casakin & Goldschmidt, 1999) acquired through a number of years spent in the domain. Considering the developmental background of the expert, the structure and organisation of knowledge and the reasoning processes of the expert, can assess expertise. Expertise in cutting tool design comes about from experiencing design cases including rare and tough cases over duration greater than 20 years.

4.3.4 Requirements of the expert

It is important for the expert to have guided other novices in the past as it shows that the expert is willing to allow a novice to elicit knowledge and not see it as a threat to their expertise. The expert needs to be familiar with the KEN process in order to facilitate the interactions with the novice. At the beginning of a task the expert needs to describe the context for which a solution is being sought and then allow the novice to solve the task. Then provide support as and when needed by the novice. This leads to the question as to whether the expert is motivated to perform the duty as knowledge provider. It would be difficult for the expert to resist the process if s/he is deemed to be participating in the process.

4.3.5 Requirements of the novice

The behaviour shown in the novice is because of the lack of knowledge about the domain. The ability to ask questions no matter how simple they are perceived by the novice is a critical element of the success of the KEN process. The major requirement for the novice is a commitment to learn the knowledge about the tasks within the domain under investigation.

4.3.6 Reducing subjectivity in the participation

Obviously, a certain amount of bias will come into the process; the novice however neutral will bring his or her own knowledge and assumptions to the process. Ball & Ormerod (2000) suggest that from a point of view of the prototypical ethnography; ten characteristics should be met. These are: situated ness, richness, participant autonomy, openness, personalisation, reflexivity, self-reflection, intensity, independence, and historicism. Whilst the author realises that all of these are difficult to be met in a study carried out in an industrial environment; however three of these relate to the overcoming of bias or subjectivity brought to the process by the novice (observer). These are: openness, reflexivity and independence. With openness, the observer should remain open to the discovery of novel or unexpected issues that may come to light as the study progresses. Reflexivity refers to the observer taking a reflective and empathetic stance in striving towards an understanding of the observee's point of view. The observer should take into account of, rather than striving to eliminate, their own affects upon the behaviour of the observees. Also the observer should remain independent; the observer must not be constrained by pre-determined goal-set, mind-set or theory.

Also relying on one expert in the process will bring a range of subjectivity to the participation process. This is not detrimental to the knowledge received but it could be argued that the expert will give you the knowledge for problems they are familiar with. For example, an expert might have a particular way of solving a problem and not consider other alternative ways of solving the problem. Thus the need to seek out solutions from many experts is suggested baring in mind the time constraints of the participation. This may be difficult to approach in industrial situations as there may be only one or two experts. However, the knowledge obtained depends on the questions relating to possible alternative solutions to the design problems should be raised by the novice.

4.4 THE KEN METHODOLOGY

Expertise or skill in any domain is acquired through a number of years of practice and is formed into special structures or categories that apply to that domain. As a result, successful knowledge acquisition will entail more than time and something other than the unstructured interview to acquire it (LaFrance, 1990). Skills are acquired in a 'learning by doing', or 'trial and error' manner (Casakin & Goldschmidt, 1999). With this in mind a more hands on approach is required to acquire this knowledge. Examining the differences between experts and novices in a domain is perceived as having a potential benefit. Knowledge = Expert – Novice is an approach to examine the nature and extent of the knowledge requiring a novice to participate in the domain of the expert. This process is shown in figure 4.1. The terms used in figure 4.1 are now discussed in turn.

4.4.1 Background and assumptions of the novice

A novice entering the domain from a graduate background is going to have a different view of the environment than that of a novice from an apprenticeship background. A more theoretical approach would be taken by the graduate whilst the novice from the apprenticeship background would a have greater practical application of the domain.

4.4.2 Background and assumptions of the expert

Being in the domain for a sustained period has probably shaped the way in which the assumptions of the expert have been defined or even utilised in the tasks of the domain. The various experiences that an expert would have gained throughout their career would be a influencing factor in the KEN process.

4.4.3 The KEN process

The KEN process starts when a novice tries to solve a domain problem. The novice will find himself or herself stuck or finding difficulty with the problem that they are undertaking. At this stage the novice must realise that they are stuck or having difficulty in solving the problem, and must be clear about the task that they are trying to solve. Following this task identification the novice needs to think about what is needed to solve the problems that they are facing. At this the stage the novice's knowledge and assumptions are used to analyse the problem that they face. Of course they may not have the basic knowledge about the domain to even begin to answer these questions. However, the KEN process is an iterative process, thus the novice may go through the cycle several times before the knowledge obtained provides the solution to the problem. Examples of the use of the KEN process are given below.

The process produces a worksheet that illustrates how the knowledge from the expert was elicited and hence can be reused when the novice faces a similar problem. The worksheet records the problem faced by the novice through a list of probe questions, the expert reply and the identified knowledge.

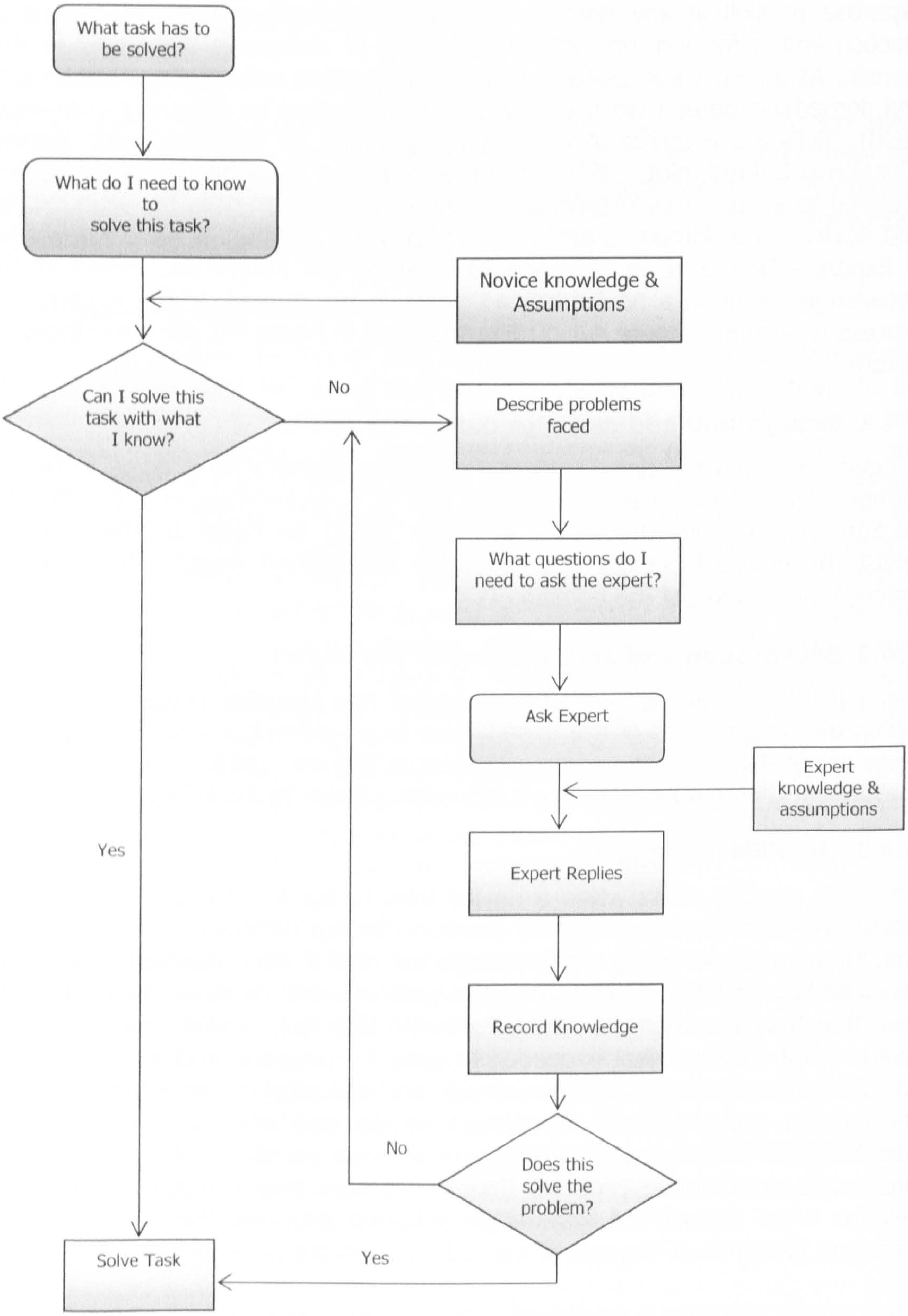

Figure 4.1: The KEN process.

Performing the task

The knowledge elicitation process starts with the novice undertaking a task in the domain. This task should be of the standard that the expert would undertake. Often the expert would describe to the novice what is required by the novice to complete the task. For example, in the domain of cutting tool design the novice is told the background of the task to be solved by the expert and the goal of the task. From here the novice will undertake the task until such time that they find themselves stuck or mistakes have been made. The aim here is for the novice to become familiar with the domain and associated tasks, so that s/he can converse with the expert when a problem arises.

Describing the problem

In order for the novice to ask the expert questions, the novice must be able to do two things; identify that s/he is stuck or experiencing difficulty, and describe the problem that s/he faces. The problem here is that the novice does not know how to bridge the gap from the brief given by the expert to the goal also given by the expert. The problems that novices face arise through a lack of knowledge of the domain, which can be further abstracted, into particular areas of the domain. The description of the problems faced should include: the type of task, area which is giving difficulty, the assumptions the novice has made and what combinations have been tested-out by the novice previously.

Listing of probe questions

From this description of the problem, a set of probe questions will materialise. The novice would know what problems he or she is having; it comes from cognitive functions of the novice. For example if a person requires information on a subject, first you have to identify the subject and then the problem areas you are having with that subject. Once this has been established a question can be asked on the subject matter for which an answer is required. The questions can be statement (summary to check information received), open (for a more elaborate answer) or closed type questions (generally provide a one word answer). It is these questions that the novice will use to get solutions to difficulties faced from the expert. However, even during this phase a certain amount of decoding on the part of the novice is required to understand the expert's language of the solution. The novice has to understand the reply given by the expert in order to utilise the knowledge in a correct manner.

Typically many of the questions that are asked by novices are of the type: What, Where, When, Why, and How? It depends on the environment and the situation as to the types of question that would be use by the novice and in what order, and thus for the methodology to remain flexible a set of probe questions is not prescribed here. In the three examples of the use of KEN there are different approaches to the use of questions.

Feedback from expert

As suggested in the previous section, an expert will provide solutions to the difficulties of the novice in their own language. The novice, therefore, has to decode this feedback before s/he can use it. A match between the questions that were asked and the reply is performed to ascertain whether the answer given by the expert was an accurate representation of the questions posed by the novice. The novice highlights the key responses from the expert and makes an interpretation of the feedback of the expert.

Identify Knowledge

The knowledge identified depends on several factors. First, the task the novice is undertaking and the problems faced by the novice from which the questions were derived. Second the knowledge level of the novice performing the knowledge elicitation. The types of knowledge that can be identified during this process are described in the next section.

4.4.5 The categories of knowledge in cutting tool design

Knowledge in design is subject to much discussion. However, through experience in the design process it has been possible to identify three main knowledge categories for the cutting tool industry: internal, external and technological. The knowledge elicited could be categorised into these three. In line with the purpose of the participation in the design process (to examine the nature and extent of the knowledge) it possible to see that these suggest certain boundaries or the 'extents' of the knowledge within the domain.

Internal knowledge

Internal knowledge is characterised by the fact that it exists within the organisation. Factors such the organisational culture would be of consideration here. The knowledge formed in an organisation would be heavily influenced by the culture that has developed within the organisation. For instance, it would shape the way in which designers would tackle the design problems given to them. An example would be the quotation process in the organisation; this would not be known outside the organisation.

External knowledge

For example, customers are external to the organisation but the designer would know what the current trends are for cutting tool materials (which the customer would know of through advertising), typical capabilities of the customer's machinery and the costs that the customer is likely to be satisfied with.

Technological knowledge

This knowledge is about the products, manufacturing processes, technical capabilities and experience of designing cutting tools. This category could exist both internally and externally. The technological capabilities of the organisation are known between its members e.g. the salesperson would know the abilities of the designers as they have been working with them for several years. Also, it is quite possible that the competitors know about some of the technological capabilities of the organisation.

In addition these knowledge types are characterised by the role that they play with the design process. Internal, External and Technological knowledge can be explicit/implicit, heuristic/algorithm or procedural/declarative in nature. These characteristics are defined in chapter two, section 2.2.2.

4.5 APPLICATION OF THE KEN METHODOLOGY

This section describes the applications of the KEN methodology. The first two examples are from the author's experiences in the tool design. The third example is the work of an individual MSc project carried out in conjunction with this research. And to show the applicability of the KEN methodology in other domains an example is provided from the Cost Estimating domain.

4.5.1 Practical cutting tool design knowledge using KEN

In the first two of the following cases, the design of the tools required the author to ask questions to the expert when the experiencing difficulties with aspects of the tool design. Thus the novice gained a piece of knowledge. The following design cases illustrate examples of both implicit and explicit knowledge types within cutting tool design.

4.5.2 Design Case One

The aim of the task was to design an end mill for the component shown in figure 4.2, which required the machining of a 5mm pocket on the backside of the component. The motion of the tool was described by the expert is as follows:

- *the tool comes in on centre with a 1mm clearance on the internal walls of the component bore,*
- *the tool then moves into position and makes the 5mm depth of cut.*

The design begins with the sketching of the machined component as shown by the hatched area in figure 4.2 from the customer's drawing. The cutting diameter of 68mm is set, paying attention to 21.50mm cut. The diameter of the shaft can set with the difference of the overall diameter and the two 21.50mm cut areas. The shank is a template that is stored on the computer system and is inserted at the point required. The KEN transcript is shown in table 4.1.

Problems faced by the novice

The author faced several difficulties when designing this component: How to start the design process, the placement and types of inserts to be used, (the constraint in this case is the size of insert that can be used due to the small size of the cutter), the size of the coolant holes and then the amount of material that is required around the inserts.

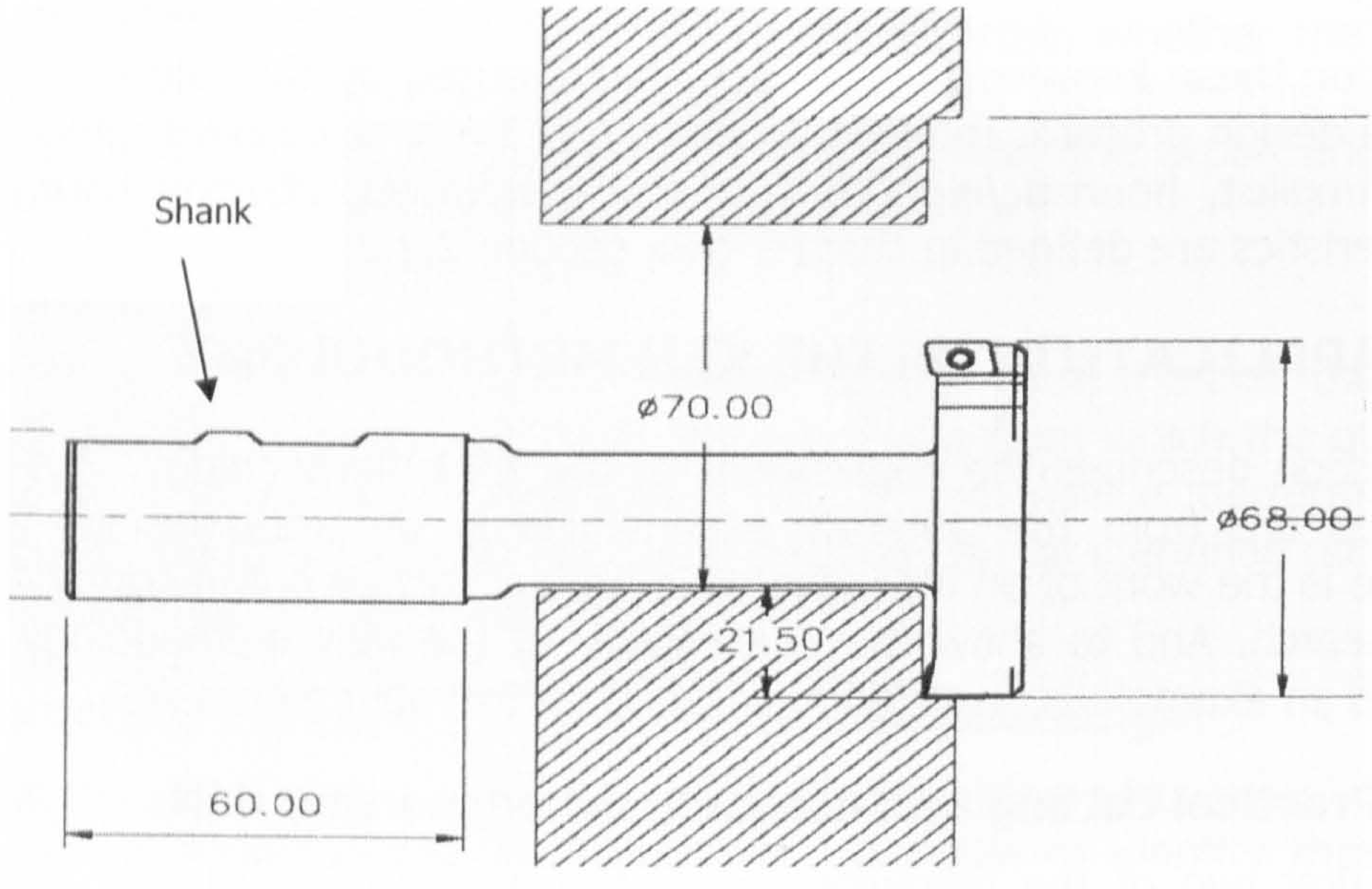

Figure 4.2: Component to be machined with preliminary design of cutting tool

Interaction & response from expert

Expert Response: Due to the size of the head of the end mill being only 9mm in section, only a particular type of insert could be used. The author found out by trial and error that the parallelogram insert shown would not do the job, after trying a number of other insert shapes the triangular shaped insert was chosen as shown in figure 4.3. It was found, that with parallelogram insert not all the metal would be cut, but with careful positioning of the triangular insert this would not be a problem.

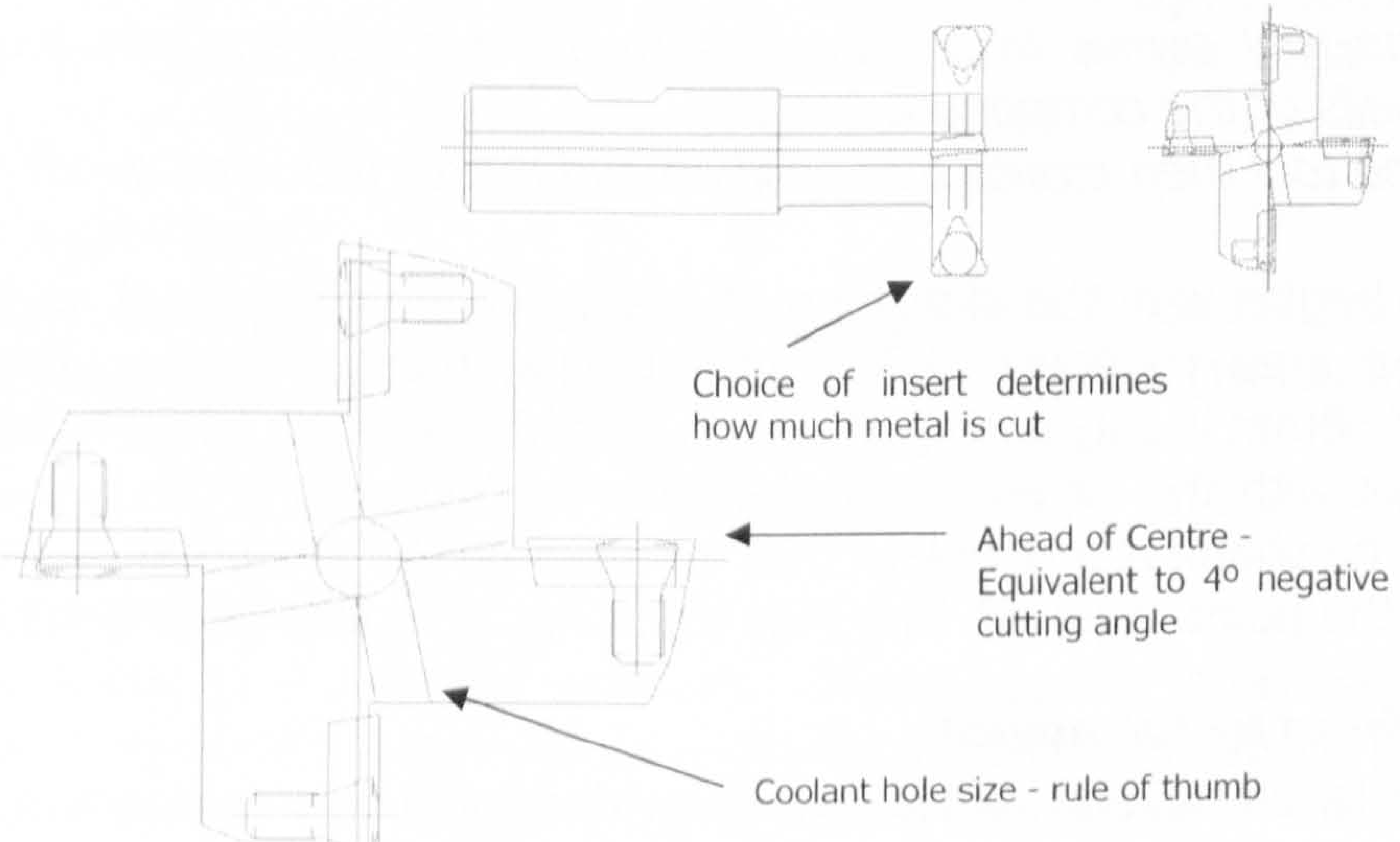

Figure 4.3: Design of milling cutter

Table 4.1: A part of the KEN worksheet for design case one.

Problem Description	Question	Reply	Knowledge
What do I have to do to begin designing for this type of cutting tool?	How to start the design?	I would generally start with laying out the component, that is draw a scale of the compoent to be machined and then place the tool in postion.	Design process, internal, technological, implict, procedural
I can see that a certain type of shank is required by the customer.	What type of shank is required?	This would be given on the proposal sheet, in this case the customer requires a DIN1835-B16 type shank.	Type of shank, ISO designations, Technological, Explicit, Declarative
	What does that mean?	It is just a shaft mounting designation/style. It has a 16mm diameter.	As above
	Where can I find the dimensions?	The template is available on the CAD system.	Use of CAD system templates, Internal, Procedural, Implicit
The expert mentioned that certain types of insert would solve the problem but I am unsure which to use and how to put them on the design.	What would be an appropriate insert to use?	Either a pallelogram or triangular insert. It depends very much on whether which of the two will remove the material completely. With the pallelogram insert I think we may have a problem with the smallest insert available. Try the design with both.	Type of Insert, Heuristic, Implicit, Trial and Error
Also, I am unsure as to what difference there is between each in the material that they cut and how this effects the design.	I have tried both inserts, which one is correct?	If you look at the pallelogram inserts it is noticeable that some of the component will be missed. The smallest available insert is 4.56 I.C. (Inscribed Circle). So using the triangular insert we avoid this problem and we can use a reasonable sized insert, 6mm I.C.	Several Insert types that requires careful selection. Internal, Technological, Trial and Error, Procedural, Implicit, Explicit
Positioning of Insert	What considerations do I have to make when deciding on the position of the inserts?	Due to the small size of the cutter, it is important to allow for the screw thread to adequate purchase. Using a neutral insert placed 4 degrees ahead of centre we can achieve a negative cutting angle.	Achieving the correct cutting condition is important. Internal, Technological

Types of knowledge identified

In this section the knowledge identified is elaborated for each cutting tool element. For example, in table 4.1 the selection of the type of insert shows heuristic and implicit knowledge being elicited by the novice.

Knowledge: The amount of material removed is determinant on the type of insert chosen and the size of that insert. *Reason*: The choice of insert is a rule-of-thumb i.e. heuristic as the novice in this is trying several inserts to achieve a solution to the problem under the guidance of the expert; his knowledge here is implicit as he suggests using different inserts as he sees potential cutting problems with each insert (see table 4.1 for the interaction on the choice of insert). Technologically, he is considering his experiences in the performance of previous designs that have had this kind of insert/material combinations. External knowledge is not encountered, as this type of insert selection and expert/novice interaction is not affected by the influences outside the organisation. Further external influences will be explored further in chapter five.

The types of inserts available to solve a particular problem are vast, matching and obtaining the appropriate cutting characteristics is vital to a successful application. This forms a part of the knowledge requirements of the cutting tool designer. The next case study highlights further knowledge requirements within cutting tool design.

4.5.3 Design Case Two

This case illustrates the requirement for more explicit knowledge available in cutting tool design. It showed the author the typical calculations to design the cutting tool in figure 4.4. The aim here is to design the toolholder for the E-Z SET unit shown in the figure. The E-Z SET unit is the feature of the drawing that contains the insert. This type of unit has a micro adjustment, which is achieved through the application of a micrometer gauge contained within the unit.

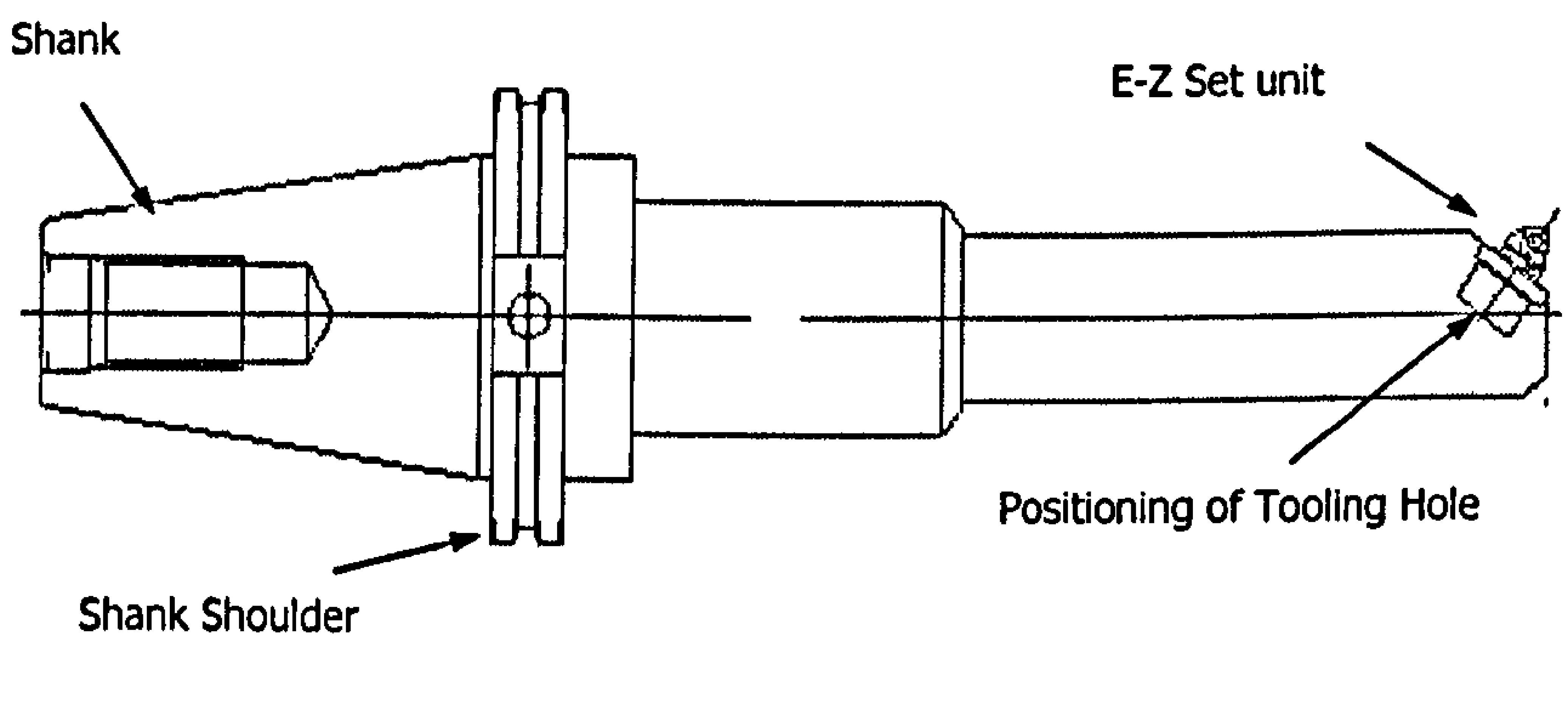

Figure 4.4: E-Z SET unit.

Problems faced by the novice

See worksheet shown in table 4.2 for the full list of problems faced by the author for this case. The main problem was with the placement of the E-Z SET unit and the design of the shank unit used to mount the unit to the machine.

Table 4.2: A part of the KEN worksheet for design case two.

Problem Description	Question	Reply	Knowledge
The problem again is about knowing where to start designing the tool given the information given	How do I go about designing an E-Z Set bar?	We have done several of these before so I would recall a previous design that uses an E-Z Set unit and adapt that to fit this proposal.	Design cases can be reused. Internal, Technological, Implicit, Procedural
The design files are kept on the system but knowing which of the files is a problem	What CAD files contain E-Z Set bars?	I seem to remember that we have done a lot of E-Z SET designs which are similar to this proposed bar. I think they are in the file folders beginning 'F' which contain finish boring bars.	As above
I am unaware of the types specific items within the cutting tool industry	What is an E-Z Set unit?	A boring unit that allows micro-adjustment in the boring diameter. The basic dimensions of the E-Z Set unit can be found in the Valenite catalgoue.	Types of tool in cutting tool design.Internal, External, Technological, Explicit
	Why do I need the catalogue?	You will need it to position the unit. You also need to do some calculations to position the tool in the correct position but also so that the hole in the bar can be machined.	Use of literature. Internal, Explicit
I have the catalogue but I am told by the expert that I need to do some adjustments to some calculations. I am unaware of the calculations	Where can I find the calculations?	The calculations are written down and kept in a file in the standards cabinet.	Types of calculation used. Internal, Technological, Explicit, Heuristic
	Why do I need to use the calculations?	The values for the E-Z Set unit given in the catalgoue do not take into account the pre-loading of 1.2mm that is required in actual use. This affects the 'x' dimensions given in the catalogue.	Reasoning for use of calculation. Deep knowledge. Internal, Technological, Implicit, Heuristic
	How we select a E-Z Set unit?	We need to select a E-Z set unit for our tool. E-Z set units are selected based on minimum bore diameter and the maximum diameter they are to cut.	Selection of components for design. Technological, Explicit

Interaction & response from expert

Obtaining an appropriate past design, which utilised an E-Z SET unit, was possible by looking through the CAD files for a finish boring bar under the designation 'F' file. The 'F' designates that it is kept in the 'Finish boring bars' file in the CAD database. This would be the way in which the expert would start the design of this type of bar. The major change to the past design would be the variation in bore diameter. This would dictate the size of the E-Z SET unit used. Product catalogues contain the E-Z SET unit information giving the critical dimensions needed in the calculation written down and kept in a file. The calculations depend on the corner radius of the insert used. The calculations give the dimensions of the bar, the bar diameter around the E-Z SET unit and the tooling-hole dimension. The shank is obtained as an object stored on the system. Upon receipt of these responses shown in table 4.2, it was possible to carry out the calculations for the E-Z SET unit and hence transfer the dimensions obtained to the drawing on the CAD system.

Types of knowledge identified

Figure 4.4 shows the knowledge identified on a special E-Z SET bar, which requires a set of calculations to be made in order to ascertain critical dimensions for it to be manufactured. The critical dimensions are shown in figure 4.5. The distance that is critical is the distance from the back-face of the shank shoulder to the 'tooling hole' which allows the pocket of the unit to be machined in at 53°8' to the centre line. The description of the calculations are given in table 4.3 which depends on the insert corner radius and the diameter of the bar into which the unit is to be placed.

Table 4.3: Typical E-Z Set calculation – Heuristic/Explicit Knowledge

1. Check your insert radius to correspond with the "X" dimension given in catalogue.
2. The "X" - dimension must have one third micro adjustment added to it.
3. To find "A" - divide bore diameter by 2, multiply that by the Cosec of 53.8°. From that answer subtract "X" dimension, which will then give the answer "B".
4. To find "D" - multiply bore radius by Cotan of 53.8°, then subtract "Y" dimension, which will then equal "D".

In the instances of explicit knowledge types in the domain the completeness of these sources varied greatly. Take for example the E-Z SET unit, it is possible to design a tool completely once the calculation is found and understood. Accessing this knowledge still remains a difficult task; as the designs do not contain the rationale that could be used in future reuse tasks. Even more importantly knowing where to find this knowledge and how to access it provides the greatest difficulty for novices and experts alike. In most cases reuse is started from the memory of the expert remembering a past design case.

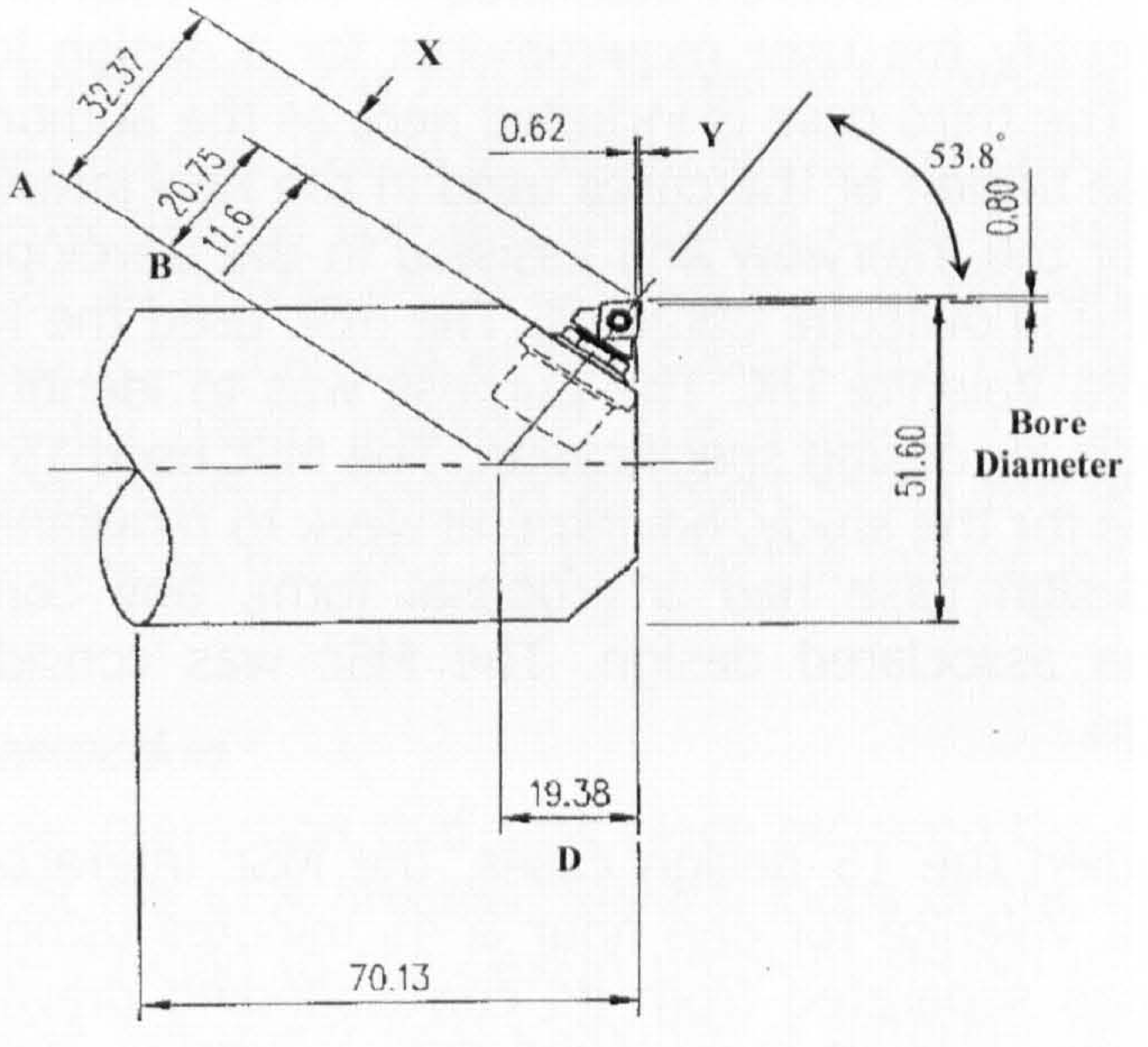

Figure 4.5: The critical dimensions on the E-Z Set unit.

4.5.4 Relevance of knowledge obtained

By undertaking designs that are for customers it is certain that the knowledge obtained is relevant and correct as designing for the customers have economic and commercial relevance for the organisation. That is, it is important for the designer to provide correct knowledge required as the tools designed by the author are to be manufactured for and used by the customer. Therefore, the tools must perform the goals and constraints set by the customer. The knowledge obtained was from one expert and thus is susceptible to some bias. However, the author while carrying out other design tasks was able to call upon the opinion of other experts within the design department to solve the problems encountered. This ensured that a wide base of knowledge and experience was obtained.

The knowledge obtained is dependent on the questions asked by the novice. Whilst it is true that the knowledge of the domain will not change but the type of knowledge obtained will be dependent on whether the novice can access it through appropriate questions. In this case the author with a background in mechanical and manufacturing engineering would be considered a typical novice of the domain. It is understandable that if a second novice were placed under the same conditions as the author, then the knowledge obtained would differ. This is because of the knowledge and assumptions that the second novice would bring to the environment.

4.5.5 Design Case Three

In conjunction with the research described in this thesis, an MSc project was carried out to identify the user requirements for a design information system (Hodges, 2002). The third case is included here as the author of this thesis was present during the design of the cases used in the KEN interview, subsequently transcribed half of the interview and assisted in the development of the MSc's organisation of the knowledge obtained. The MSc used the KEN approach with an expert at Widia Valenite UK. The purpose was to identify a correct design solution to a particular design specification. The MSc used 15 designs chosen at random as a basis for the study, having one week to familiarise himself with the designs. Each design case had a proposal form, any component drawings available and the associated design. The MSc was considered a novice to cutting tool design.

After having studied the 15 design cases, the MSc interacted with an expert designer at Widia Valenite for one hour & 45 minutes using the KEN process. Each proposal was separated from its corresponding drawing. The drawings were then placed on a table in a random order. The novice and the expert designer interacted based on the proposal form to identify the features and attributes that the expert would use to recall a previous design. This interaction was videotaped and then transcribed to analyse the knowledge obtained. The transcript was then organised through the worksheet shown in table 4.4. The author analysed this case from a validation point of view to reduce the interpretation bias in the KEN methodology.

Recalling a past design solution

The purpose of this study was to utilise the KEN process to enable the selection of a correct design solution to an existing design case. This process allowed the novice to elicit the appropriate knowledge in the form of features or attributes that would enable this selection from the initial information provided by the customer (the proposal form). As in the majority of design cases (including the 15 selected here) the information provided by the customer is scarce. Therefore, expertise that goes into selecting a design for reuse is required. Engaging with an expert having the knowledge and experience of the analysis of the problem and allowing him/her to work with what information is available, the essential features of the design solution are obtained. The following describes one such expert/novice interaction. Each design was decomposed in the same way.

Novice observations of the design case

From the familiarisation of this particular design case it was obvious to the novice that all that could be determined from the proposal was the need for an insert to produce a series of grooves on a spanner shaft component. Also apparent from the proposal were the dimensions that the grove is supposed to take. For a novice to select a past design case to begin the design process is very difficult – the question is where to start?

Assumptions and knowledge the novice brings to the process

The novice assumes that he needs to obtain some knowledge from the expert for the missing items that he can use to search a design database with. The MSc recognises that an important consideration is in knowing the component material. This is from his learning of the cutting tool domain through video, academic and industry based literature. The material to be machined is an important consideration when choosing an insert to cut the groove. Identifying this, as knowledge needed the MSc undertakes the interaction as follows in the next section.

Expert/novice interaction

Table 4.4 shows the interaction that took place between the expert and novice in this application of the KEN process. Several loops of the KEN process were used to obtain the solution to the design problem shown in the bottom right hand corner of table 4.4. Each loop identified a different piece of knowledge that led to the identification of the problem solution. The loop is initiated by a description of the problem faced by the novice. The novice asks the expert the derived questions. The expert replies and at this point the novice records the knowledge obtained. A full transcript of the interaction between the novice and the expert is shown in section A2 of appendix A.

Identification of features and attributes

The knowledge obtained in each summary table obtained for the 15 design cases were then decomposed by identifying features and attributes in the tables to enable appropriate selection of the design case in a reuse situation. These were then placed in a hierarchy of Application, Component and Tooling. This hierarchy is described further in chapter six of this thesis. For example in the transcript mentioned above the feature of the insert requiring a negative geometry in order to be strong enough to cut steel is part-of tooling in the hierarchy. Armed with this new knowledge (features and attributes identified in the KEN interaction) the novice then selected the appropriate design for the particular proposal form for the design case concerned as laid out on the table.

4.5.6 Use of the KEN methodology in cost estimating

Rush et al (2002) have utilised the KEN methodology in the domain of cost estimating. The author participated in the design of the knowledge elicitation experiment for this case. With prior experience of the domain gained through an IDEF0 modelling process Rush et al were able to acquire an overview of the domain prior to using the KEN methodology. The process was carried out with cost modelling experts whom described how the cost estimate worked, and the novice documented the information. The KEN process was documented on a set of four templates, which relate to the stages in the KEN methodology described in section 4.4.3. These are describing the problem, listing of probe questions, feedback from the expert & novice interpretation and finally the identified knowledge.

Table 4.4: Interaction between expert and novice for design case three.

Loop	Description	Question	Reply	Knowledge	Problem Solution
One	Looks like a grooving task has to be performed. I do not know what material has to be machined.	What material has to be machined here?	This is some kind of spanner shaft so it is going to be steel.	Spanner shafts are likely to be made from steel. Assume that the material to be machined is steel.	
Two	I am wondering how the 30 deg. form to the grooves will be formed.	How are the 30 deg. teeth produced?	Use a triangular insert and put a 30 deg. form on the front.	The form required on a machined part can be produced by replicating that same form on the insert.	
Three	I know the form of the insert, but what about the other insert geometry details.	Should a TNEC or a TPEC be used?	Use a TNEC32 because you are cutting steel.	Using an insert with a negative geometry will provide the strength required for machining steel.	
					Look for a special grooving insert with a 30 deg. form and a negative geometry.

Description of the problem

The example task analysis presented in figure 4.6 focuses on the calibration process called ECIRP, which is simply PRICE spelt backwards (Rush et al., 2002). The task of the novice in this case was to calibrate the cost model using ECIRP, which required the elicitation of knowledge to complete the task for air vehicle general systems.

Task Analysis Worksheet	
Task	Calibrating the PRICE H cost model
Organisation	The calibration process is an essential part of the company's new product cost estimating process.
Goal and Value	The goal of the calibration process is to align a commercial off the shelf parametric cost model (PRICE H) to recognise the companies anticipated performance. The expected costs are based on historical product and cost data, and internal estimates. The value of this process determines, from a cost perspective, whether both the company and customer requirements are realistic and achievable.
Dependency and Flow	***Incoming*** - The calibration process depends on the collection and use of data, information and knowledge. The main types of data used are: historical, technical, operational analysis, external parameter, and external company data. Knowledge and experience is required in order to know what data to obtain, where to collect it, why it is needed and how to interpret it. ***Outgoing*** - The outputs of the calibration process are a cost model that can be used to produce the required estimates for similar variants. The air vehicle cost estimates can then be fed into a support cost model so that a full life cycle cost can be delivered to the customer.
Objects handled	***Incoming*** - Customer requirements, software cost estimates, wind tunnel cost estimates, operational analysis data, product definition data, mass statements, historical data (electronic, and paper files), process improvement data, and external company data (see Figure 4). ***Outgoing*** - cost estimates for the Air Vehicle and supporting documentation.
Time and Control	***Frequency*** – Variations of the original calibration data set has been in use for five years on all subsequent variants of the new product. ***Duration*** - The original calibration process took approximately six months to complete. ***Control*** - Data is supplied from both internal and external company estimates. The company has more control on the internal data sources. Designing new advanced military aircraft does not happen often. Therefore the processes used currently are not likely to be the same as those used historically or in the mid to distant future. Hence, control is difficult as procedures, processes and objectives constantly change through time. ***Constraints*** - The main constraints centre on the lack of validated data. Internal calibrations are based on a limited number of sanitised data sets. Therefore, complexity factors used in calibration may not be appropriate to future applications due to "grey" product definition, which can change in nature significantly as product maturation proceeds. In addition, 'future' cost forecasts are being developed before 'current' performance is fully understood
Agents	The estimators are the chief agents of this process they rely on assistance from engineering specialists to supply necessary product data.
Knowledge and Competence	Core competencies include the ability to request and interpret all data sources. The ability to use the PRICE H cost model and the spreadsheets. The ability to make judgements concerning the new product in relation to historical data. Furthermore, a broad understanding of current processes and future process improvements
Resources	Meaningful data is key to cost estimating success.
Quality and Performance	Review gates and meetings help to keep work on track to ensure targets are met.

Figure 4.6: Example of task analysis sheet (Rush, Bailey & Roy, 2002).

Table 4.5: List of probe questions and novice interpretation (Rush 2002).

Establishing the value of WS		
Probe ID	**Probe Questions**	**Knowledge**
P1	What do you do?	We need to establish the percentage of structural mass (WS), and the percentage of electronics mass in relation to the total mass.
P2	Why would you do this?	All systems items require the total mass to be divided into structural and electronic mass. The cost model estimates a higher cost for a system that contains a high percentage of electronic mass.
P3	When would you do this task?	The WS function is performed on all systems.
P4	How would you do it?	Firstly, the estimators work with the systems engineers to establish an estimate of the values. This would normally be a percentage e.g. 80% structural mass and 20% electronics mass. Secondly, the actual mass values are calculated in an Excel spreadsheet. Finally, these values are input into the cost model. The same values derived for the calibration data set have been used on all product variants.
P5	Why do it this way?	The spreadsheet is used for calculation and recording purposes. The validity of the percentage split should be validated for each product variant but is not due to time constraints.

In figure 4.6 the task breakdown is shown in order to calibrate the cost model and the sub-tasks were identified. Each of these sub-tasks requires knowledge to be elicited and as the novice was new to the domain; several questions needed answering. Table 4.5 illustrates the probe questions used and how they were used to interpret the expert's knowledge.

Identification of knowledge

The final template completed by the novice is presented in table 4.6. It describes the nature, form, and availability of the knowledge for each subtask. This template illustrates that much of the knowledge required to input the WS values is based on assumptions and there are several bottlenecks. This form was verified with the experts from whom the knowledge had been acquired. The next section summarises the results of using the KEN methodology in the three examples shown.

Table 4.6: Identified nature, form and availability of knowledge (Rush 2002).

Mass of structure in relation to electronic mass (WS)	
Comments: WS relates to the structural mass as a percentage of the general system electronic mass. For example, with respect to the total Hydraulics mass, 80% is assumed structural mass and 20% is assumed electronics mass. With respect to the total Flight Control Systems (FCS), 80% is assumed structural mass and 20% is assumed electronics mass. The percentage split resulting from this assumption can have a significant impact on the final costs of the product.	
Nature knowledge	**Bottleneck/area to improve**
Formal, rigorous	
Empirical, quantitative	
Heuristic, rules of thumb	This measure is only used on the General Systems such as Hydraulics (80% structural mass, 20% electronic mass), and FCS (75% structural mass, 25% electronic mass).
Highly specialised, domain specific	
Experience-based	The WS is first calculated in an Excel spreadsheet before being input into PRICE H.
Action-based	
Incomplete	
Uncertain, may be incorrect	The WS value is based on the estimators and/or engineering judgement.
Quickly changing	
Hard to verify	The chosen values are assumed.
Tacit, hard to transfer	Not possible to understand how the values were chosen there is no record of why these assumptions have been made.
Knowledge Form	**Bottleneck/area to improve**
Mind	There is no empirical justification for the chosen values.
Paper	The values are printed and archived.
Electronic	The values are input into the Excel spreadsheet and the PRICE H model.
Action skill	
Other	
Knowledge Availability	**Bottleneck/area to improve**
Limitations in time	
Limitations in space	
Limitations in access	
Limitations in quality	The chosen values are based on the estimators subjective judgement.
Limitations in form	

4.5.7 Knowledge capture with KEN

This section provides a qualitative evaluation of the experiences of using KEN against the criteria set out in section 4.2. As with any 'on-the-job' learning based approach, the novice learns about the nature of the knowledge requirements for cutting tool design by actively undertaking typical design tasks. Thus, the KEN methodology requires the novice to participate in the domain of investigation. As a result the behaviour of the novice has been shaped and modified to suit the environment while interacting with the expert. As illustrated in this chapter, the knowledge requirements for industrial tasks are complex, incorporating several different types of knowledge including technical and commercial knowledge. The knowledge required exists in several places, as localised items used when required depending on the design task.

Structured approach

The methodology provides a structured approach to the capture of task based knowledge in cutting tool design and the cost estimating process. It does by virtue of a structured elicitation process with identifiable steps and a recording procedure to identify the knowledge in these tasks in the interaction between the expert and novice. The KEN methodology was seen to provide a very useful structure for the elicitation of knowledge and information requirements in connection with cutting tool design. The elicitor undertaking the task of the expert highlighted real problems faced in identifying design solutions. This allowed a clear statement of the problem faced by the elicitor to be made at each stage of the elicitation process, thereby leading to the elicitation of the most relevant data.

In the first two design cases it was the structured approach to interacting with an expert that helped the author to elicit knowledge he could use time and again. At first it was useful to try and perform the design himself and then if there were problems, he found that writing down the problem helped to articulate his thoughts. This allowed the author to formulate questions that were relevant and understandable to the expert and hence the creation of a valuable elicitation process. Having the approach clearly defined, the author found that his learning improved quickly and significantly. This was apparent in the undertaking of more complex design tasks.

Record of Interactions

The record of interactions provides transparency of the knowledge obtained. This has been observed in all four cases described in this chapter. The MSc individual was able to use his records for interaction to build tables that categorised the knowledge he had found. This record provided him with a tool that facilitated the identification of features and attributes that were later used in the determination of key searchable terms. The author was able to use his recorded interactions to solve further instances of cutting tool design.

Identify key task information and knowledge

Rush (2002) found that the KEN methodology illustrated that expert judgement was extensively used to operate the cost model, but underlying assumptions and rationale were not made explicit to future users and that KEN highlighted the knowledge intensive areas of the cost modelling process and areas for future development. The knowledge elicited by the MSc individual was the key knowledge to identify terms in a set of proposal forms which lead to the derivation of a set of natural search terms for designers in their reuse activities.

The novice learns form these interactions

The author repeated similar tasks during his participation in the design process. He was able to use the structured information in the worksheet again. For example the author carried further designs for the E-Z Set variety of cutting tool. In this case there was less reliance on the expert to solve the design problems. In the case of insert selection the author found that his awareness of the issues raised for insert selection helped him to select inserts with more autonomy. However successful further applications of the knowledge gained meant that the reliance on the expert/s is difficult to avoid.

Contrary to this was the view of the MSc individual. He found that the knowledge obtained for the first set of designs he examined did not help him select the correct design in the second five cases. In the first five cases the knowledge elicited gave him the lacking background knowledge (terms & jargon) that is required to even begin to design a cutting tool. In the second case he found that he had not experienced enough of the domain in order to decipher the second set of proposals. Introducing a set of terms that he wasn't aware of caused problems, which he was not able to overcome without further interaction with the expert/s. However time and resources were not available to test the KEN process further.

A generic approach

The applicability in another domain has been shown to be a success. It was applied to the cost estimation exercise of calibrating a cost model. The user of the KEN approach in this case was able to gain a useful level of knowledge from the expert in the domain to solve the problems he faced. The applicability has only been tested in one case from another task-based domain. The author does realise that based on this one case it cannot be warranted that it will work in all task-based situations. However, the potential of the methodology has been demonstrated for other task-based domains.

4.5.8 Comparison of the KEN methodology with other Knowledge Elicitation techniques

This section compares the knowledge elicitation of the KEN methodology as compared to other knowledge elicitation techniques. As there has not been any testing with the other techniques for eliciting the knowledge described in this chapter; one can offer a qualitative summary of strengths and weaknesses of the KEN methodology against the other techniques.

KEN requires the novice to actively participate within and expert's domain. The novice is therefore able to acquire the tacit task knowledge of the expert by being actively involved in the domain of the expert. It is this interaction that separates KEN from other knowledge elicitation techniques which enables novices to obtain through trial and error, the task knowledge for a domain.

The 'between' communication problems of expert/elicitor not having a common domain language that manifest in other techniques have been overcome with the KEN methodology. This is because the elicitor has had an experience in the domain and has enhanced his understanding of the domain. This reduces the communication obstacle from the interaction and this will continue to improve as more interactions are undertaken. This is where the limitation of protocol analysis becomes apparent. The difficulty with protocol analysis is not having any prior knowledge of the domain during elicitation.

The MSc individual found that this prior domain knowledge helped his ability to understand the domain better during elicitation. He quotes about KEN: *"firstly, without this prior knowledge, initiation of the process would not have been possible"*, and he continues: *"the process must start with the novice (elicitor) being able to formulate in his head an understanding of what types of information he needs to have in order to complete the task, which in the context of this work is the identification of the correct design solution from the original design specification. A lack of familiarity with the terms used in cutting tool design would have made this impossible"* (Hodges, 2002). Also any misunderstandings in the language of the domain can be minimised or even eliminated as the expert and elicitor are solving the same problems on a day-to-day basis.

The KEN methodology overcomes the problems, which are apparent when straight articulation of knowledge is elicited from the expert such as in structured interviews. The nature of the structured interview requires the elicitor to have prior knowledge of the domain. Also there is a further problem with structured interviews, if the knowledge has become routine to the expert and thus s/he is going to find it difficult to articulate. This is overcome in KEN because the expert is being taken through the exercise and thus the expert can see through the eyes of the novice and identify knowledge that may have been overlooked in the straight elicitation. And hence the expert is also learning how to articulate his knowledge because he sees the difficulties faced by a novice if the knowledge being given to the novice is not articulated properly. The unstructured interview is beset by problems of knowledge that lacks continuity or being inconsistent. The KEN methodology provides a structured framework that can over these deficiencies.

The KEN methodology suffers the same limitation of the time taken to achieve a suitable level of knowledge as per the cognitive interview. In KEN the number of iterations or repeated questioning of the KEN process will govern this factor. The ability of the elicitor to understand the knowledge given as the problems become more complex also comes into question. As with the cognitive interview the KEN process is benefited by the knowledge elicitation-taking place in the workplace. Thus the expert can recall feelings as the design cases or designs are explored because the stimuli experienced during the past design can be recreated.

A further limitation of the KEN methodology is the subjective interpretations of the novice, which means that results, obtained from the KEN process could be challenged. One can overcome this by using multiple experts in the separate interactions. The very experts that have given knowledge in the first place can also reduce much of the subjectivity because the use of the worksheets and templates that are used to record the knowledge can be verified. Another expert or experts in the domain could also perform the KEN process on the task that was initially performed by the first expert. This will add a triangulation effect to the process. However the time taken for this extra interaction is unlikely to be available in an industrial environment.

4.6 SUMMARY & KEY OBSERVATIONS

In section 4.1 the views of other cutting tool industry as to the nature and extent of design knowledge was presented. It was noted that in the design it takes several years to become proficient at the task of design. And as such requires the novice to work closely with the expert.

Section 4.2 presented the criteria for a methodology to capture design knowledge. The key criterion is the need to identify task information and knowledge in a structured manner applicable in other task based domains.

The development of the KEN methodology was described in section 4.3 stating the key motivation for the development of the methodology. During participation in a typical design process of the cutting tool industry to author found himself faced with difficulty or stuck with a design task he was carrying out and hence required the interaction of the expert to impart his knowledge to the novice.

The KEN process was outlined in section 4.4. Four stages to the interaction process have been described: definition of the problem, question generation, asking the expert and interpretation and identifying knowledge.

Section 4.5 the KEN methodology was applied in task based applications in the design situation. It was found that the process provided a structured process highlighting the key information and knowledge in the tasks. Furthermore it was illustrated that the methodology can be used in another domain with an example from cost estimating. It was also shown that KEN overcomes some of the problems with other knowledge elicitation techniques.

The KEN methodology is used next for a detailed study of the knowledge requirements of cutting tool designers at the preliminary design stage as described in chapter five.

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CHAPTER FIVE

Knowledge requirements for special purpose cutting tool design

5.0 INTRODUCTION

The previous chapter highlighted the nature and extent of special purpose cutting tool design knowledge. This chapter studies in depth the knowledge requirements at the preliminary stage of the design process and continues the use of the KEN methodology developed in the previous chapter on industrial case studies. Providing designers with complete design knowledge would answer all questions and eliminate the need for unsupported decisions being made when designing a product. However, industry based design problems are complex and involve a variety of knowledge requirements which are often unavailable or simply missing.

Knowledge requirements of designers vary with the level of product complexity involved in the design. In most cases even if the product is perceived as having 'low complexity': it still requires a baseline level of information for a designer to design the product. It follows that if the perceived complexity of a product is high then more information is required to design the product. Information provision will vary according to the level of design involvement as the more complex a product the more information will be required to design the product. The author has observed many instances when incomplete proposals have been given to the expert, and he has subsequently spent time sourcing this missing information. It is also noted that complete design information is not likely to be available as not everything is known at the initial stages of a design project. The aim of this chapter is to investigate in depth the knowledge required in special purpose cutting tool design at the preliminary design stage.

To achieve this aim, the section 5.1 examines the roles and types of knowledge in special purpose cutting tool design and an initial categorisation is proposed for the types of knowledge in the domain. In section 5.2 a matrix approach to identify the knowledge requirements of designers by identifying problems & subsequent questions for the preliminary design stage is discussed. Section 5.3 the matrix approach is applied at the proposal stage of the special purpose cutting tool design process. The benefits from using the approach for the collaborating organisation are discussed in section 5.4. Finally the chapter is concluded in section 5.5 with summary and key observations.

5.1 KNOWLEDGE IN CUTTING TOOL DESIGN

This section describes the initial study on the roles and types of knowledge in special purpose cutting tool design. The participation of novices in special purpose cutting tool design has identified the roles & types of knowledge in the domain. These were then organised into an initial categorisation representing the types of knowledge within special purpose cutting tool design. The next section describes the special purpose cutting tool design lifecycle.

5.1.1 Product lifecycle

The designer leads the special purpose cutting tool design development lifecycle. The development lifecycle is shown in figure 5.1. It is noticeable that the cutting tool life cycle is design-driven as depicted in figure 5.1. This means that design knowledge is key to the whole process with typical design lead times from 2 hours to 4 days depending on the complexity of the product to be designed.

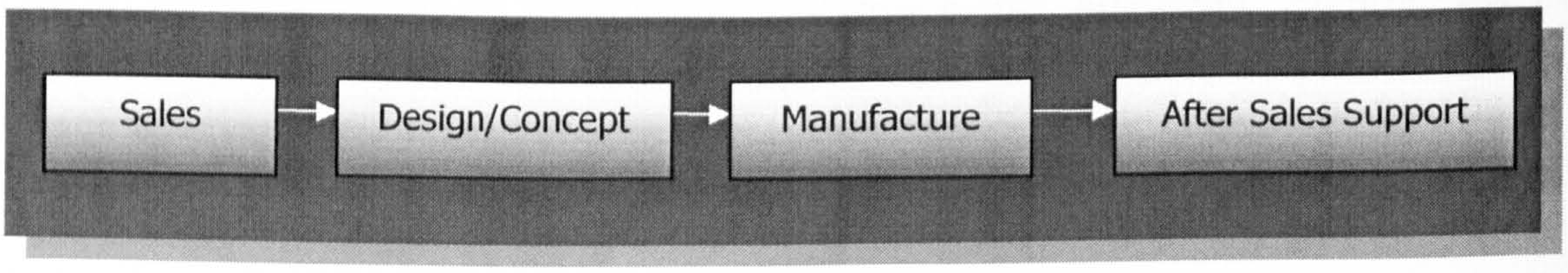

Figure 5.1: The lifecycle of special purpose cutting tool design.

The designer receives from sales a proposal request, upon which a design is produced and if acceptable (customer approval) the detail design work is carried out. The design is then sent to manufacture, and any problems regarding manufacture are advised to the designer. The sales force visits the customer during the after sales phase but any problems are related back to the designer in each case. At each stage design knowledge is used. Sales use internal, external and technology based design knowledge to assess the problem of the customer. The assessment includes the understanding of the problem demonstrating a use of engineering knowledge based on whether the designers can design what they propose – this comes from experience that has been built within the organisation. They are also aware of the competitor's products and design capability thus showing use of external knowledge (outside the organisation). The manufacture of the cutting tool is performed from the specifications set out by the designer knowing the capability of the out-sourced manufacturer. The design process drives the manufacture of the cutting tool.

5.1.2 Case studies using KEN

Three cases studies in cutting tool design were illustrated using the KEN methodology in chapter four (see section 4.4). Two cases were from the work of the author and the third was the work of an MSc individual project which was supported by the author (Hodges, 2002). The next section summarises the examples of knowledge obtained from all three cases as an illustration of the roles and types of knowledge in cutting tool design.

Example of knowledge identified

For the first case table 4.1 in chapter four (see section 4.5.2) shows the design process knowledge obtained from the expert during the authors participation in the design process. The author has classified this knowledge into internal, external and technological types. Internal knowledge: the design process for the sponsoring organisation is kept within the organisation and is very implicit. The author found that the procedural steps that are followed to achieve a design are known through experience of designing. The development of a design from proposal form to final design required the author to interact with the expert designers to select components that were required in the design. Further internal knowledge revealed that the designers used heuristics to develop their designs. In particular, the designer performed sizing of coolant holes by understanding the operational requirements and judging that a certain size will fit the amount of coolant required. This shows an example of technological knowledge that is a rule of thumb and hence remains implicit until known through experience. On the second case (see section 4.5.3) demonstrated the use of explicit knowledge that was a recorded procedure. However, the designers had an additional trick to achieve the design of the E-Z set unit, which was not recorded. Again this was individual to each designer and as such was heuristic in nature.

For the third case using KEN (see section 4.5.5) the example shows that three types of knowledge were extracted from the designer. The types of knowledge identified as shown in the following:

1. Spanner shafts are likely to be made from steel. Assume that the material to be machined is steel.
2. The form required on a machined part can be produced by replicating that same form on the insert.
3. Using an insert with a negative geometry will provide the strength required for machining steel.

These are very much technological knowledge types. The first demonstrates the use of engineering science knowledge. The problem for the novice in this case was that no material information was given on the proposal form. The expert's response to the novice was: *"because the work piece was a spanner he could assume that the material was steel"*. A common manufacturing process in the cutting tool industry is demonstrated in point 2 in the list above. This is also external knowledge, as the designer would have to know of the supplier of form wheel, which would grind the 'form' on the insert. And finally, the technology on the insert would be an external type of knowledge also as competitors would have the same types of insert. The designer would be aware of the customer's capability. The next section summarises the knowledge obtained during the KEN exercises.

5.1.3 Types of knowledge used in cutting tool design: An initial categorisation

Several authors have identified and proposed key knowledge needs of designers as cost, time, quality and environment (Cantamessa, 1997). Rodgers & Clarkson (1998) suggest that there are likely to be many other factors, which affect, and are affected by, these four key needs. The method-developed aims at arriving at a possible solution to a design problem by identifying primary knowledge need, the secondary knowledge need and then subsequently identifying the types of knowledge, which are required to satisfy those needs. However, as described above, the knowledge needs of the designer may require several of these knowledge needs and often they are intertwined. Furthermore, in the cutting tool design domain, the complexity is increased because of multi-variable geometries, process and material combinations that are available for every design problem considered by the designer. For every component there are a multitude of insert geometries and processes available to achieve the shape and form required. Choosing the appropriate combination of insert and process to a material requires knowledge gained over several years of experience.

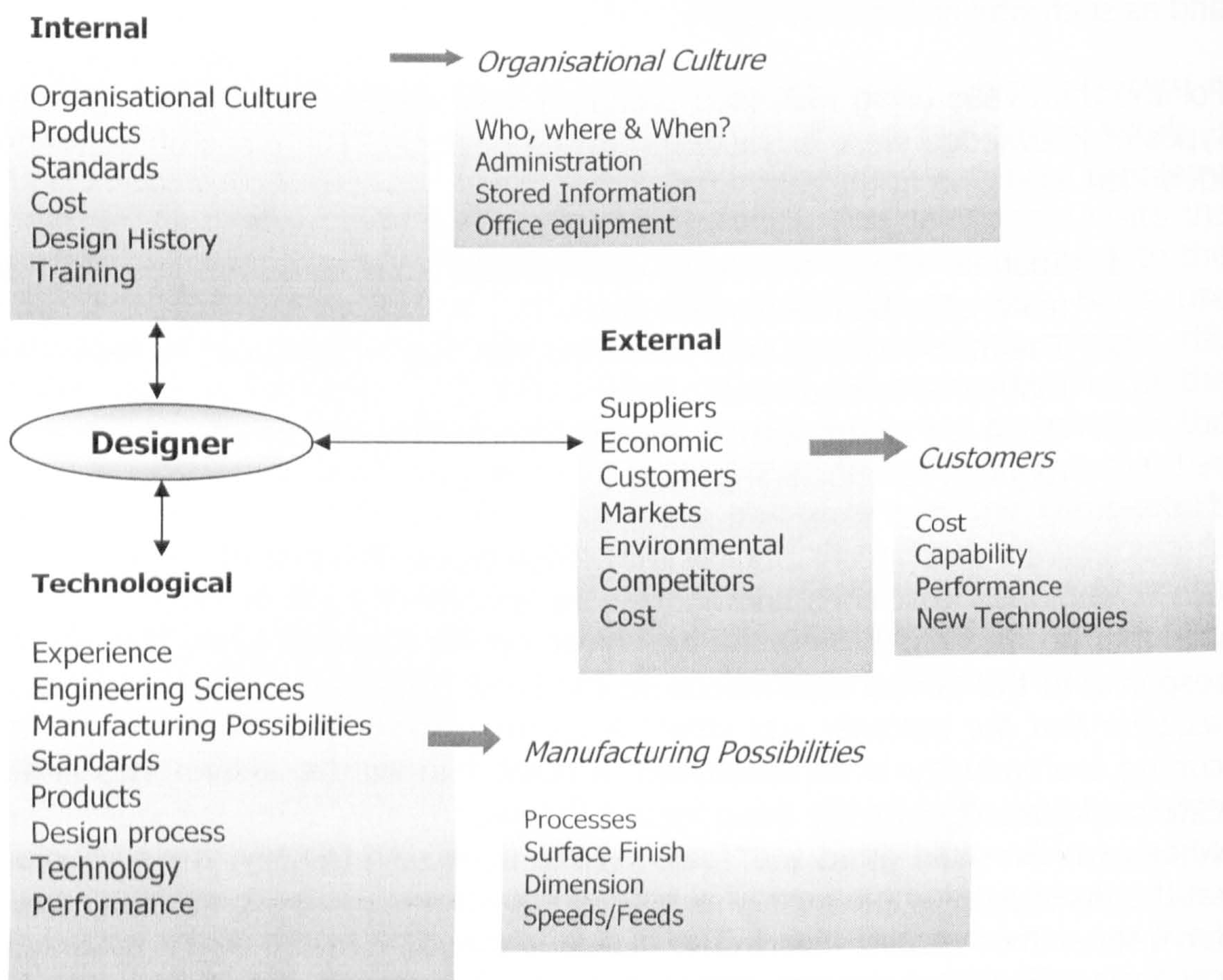

Figure 5.2: Types of knowledge required in cutting tool design (Bailey et. al, 2000).

Cutting tool design is a knowledge intensive process. At every stage in the design process designers need knowledge to complete their tasks. The pace of political, economic and technological change means that the design environment has become more challenging. It is now important that a designer considers a wide range of issues when designing in order to continuously innovate and keep up with the increasing competition. In addition to technical knowledge (past designs, materials, manufacturing knowledge and standards etc.), the designer must consider external (outside the organisation) and internal (inside the organisation) knowledge. These types of knowledge are shown in figure 5.2. A designer needs a basic knowledge of each of the items mentioned in figure 5.2. Each of the knowledge types can be broken down into more specific knowledge types as shown with customers, organisational culture and manufacturing possibilities. In the knowledge type 'customers', the designer would know what the current trends are for cutting tool materials (which the customer would know of through advertising), typical capabilities of the customer's machinery and the costs that the customer is likely to be satisfied with.

Figure 5.2 was developed by experience of the cutting tool design domain. Each term was used during interaction with the employees at the sponsoring organisation. These were recorded and later grouped into three categories. The term technological was influenced by the same term in PEST (Political/legal; Economic; Socio-technical; Technological) analysis (Johnson & Scholes, 1999). The terms internal and external were influenced by the internalisation and externalisation of knowledge in organisations described by Nonaka & Takeuchi (1995). The activity of designing demands a very broad and varied set of information (Hubka & Eder, 1990). A selection of characteristics for the design activity is given including knowledge of engineering sciences and manufacturing possibilities. The research presented in section 5.1 looked at the requirements of the special purpose cutting tool designer by novice participation using the KEN methodology. An initial model of the designer's knowledge requirements based on this interaction has been presented. The next section discusses the identification of knowledge requirements of cutting tool designers in detail.

5.2 IDENTIFYING THE KNOWLEDGE REQUIREMENTS OF CUTTING TOOL DESIGNERS

This section describes the framework for the identification of the knowledge requirements of cutting tool designers. During the investigation of the cutting tool development lifecycle the information for the designer to perform his task was given at the proposal stage i.e. the sales/design interface. The author investigated the knowledge requirements of the designer by looking at the proposal documentation, which includes a proposal form and a component drawing.

The proposal stage being the value added activity of the design process is initiated mainly by a salesperson visiting a customer and taking an initial look at the perceived problem. It is the sales engineer's job is to understand what the customer perceives as a problem. He/she then transfers this perception in terms of goals and constraints to the proposal form. In many cases the salesperson may suggest a solution and supply the completed form, with any component drawings and/or existing tooling specifications. An example of a 'well-filled-out' proposal form and correspondingly a 'poorly' filled out form are shown in appendix B, section B1.

The objective of the study was to examine and understand the nature of the knowledge requirements of cutting tool designers at the proposal stage and develop a framework to capture the knowledge and hence facilitate its reuse. This would highlight the knowledge that is required and therefore must be captured during the design process.

A matrix approach to study and understand the knowledge requirements of the designers was proposed. It was noted through participation in the design process that there were different levels of design undertaken by the design department depending on the complexity of the component to be machined. This varied from the reissue of an existing design to an innovative design for the organisation. Furthermore, it was recognised that each level of design required different activities to be undertaken by the designers to achieve a design. The approach provided a mapping from the product types identified by the salesperson, to the identification of problems by the designers via the types of design and the design activities carried out by the designer.

For this study two salespersons were randomly selected, each having 20 years experience in the cutting tools industry; two designers were involved in this study: an expert with 20 years experience in cutting tool design, a novice with 3 years experience and the author (background in manufacturing & mechanical engineering).

5.2.1 The matrix approach

The following sections describe the steps in the matrix approach that was used to analyse the design process. At each step of the methodology either the expert, novice or both are required to analyse the design process. Thus, each heading illustrates the interaction at each step by the expert and novice designated by the **E** & **N** respectively.

Identify Knowledge in Design (N) & Key Value Added Task (N)

The KEN methodology is used here to identify knowledge in the proposal stage of the design process by actively creating designs within the design process. To become familiar with a domain it is likely that around 20 designs should be completed. Identification of the key value added task requires documentation relating to the task to be collated for the categorisation in the next phase of the methodology. The requirement here is to collate what the designer would actually receive or work with during the initial stage of the design process.

Categorise based on design type & validation (N)

The forms collated from above are arranged according to the design type perceived by the novice by looking at each individual proposal form and assessing how complex the design task is likely to be based on the information given. A classification for design type is developed to provide a guide for the experts to use in the following interactions.

Identification of common problems by designers (N, E)

Novice and expert designers were asked to highlight problems faced when they received the above-categorised forms. Each interviewee was asked to describe, "How they would proceed to design the product based on the information given?" This gives a comprehensive list of problems faced by a designer when trying to perform design work from a given set of requirements. Each problem was recorded on a 'post-it' note and stuck down on the proposal form that relates to the problem. This kind of questioning leads to the designer giving information on process, calculations and design methods that are required in the product design process.

Identification of activities for different design types (N, E)

A matrix to describe the relationship between each design type against design activity is shown in figure 5.3. The design process must be decomposed into the activities required to design the product.

Design Type (T1, T2, T3...)	Design activities (D1, D2, D3...) →			Score
	T1, D1	T1, D2		
	T2, D1			

Figure 5.3: Design involvement 'T' versus design activities 'D'.

Figure 5.3 shows design activities (D1, D2, D3...) undertaken by the designers for each design type (T1, T2, T3...). An 'X' would be placed in a cell where a design type requires some design activity to be performed to design the product e.g. corresponding T1 against D1.

Relating problems to design activities (N, E) & Impact analysis of problems on tasks (N, E)

Design activities (D1, D2, D3...) are related to problems (P1, P2, P3...) in similar ways to that of figure 5.3 e.g. each design activity (P1) can correspond to many problems (P1) faced by designers. Again a matrix is used to assess which problem is influential on particular design activities. For example the design activity D4 'Assessment of cutting tool parameters' (see 3rd column of table 5.1) is related to Problem P1 (see 4th column of table 5.1) 'Dimensions of component'. This means that in assessing the cutting tool parameters the designer requires the dimensions of the component to complete that activity in the design process. An impact analysis is performed in this case with a rating of High (5), Medium (3) & Low (1) being assigned to cells on the matrix where the design activity is related to a problem and the designer requires information based on this interaction. In the relationship described between D4 and P1 the impact of this information missing during this design activity is 'M' or a rating of 3. Both expert and novice perform the task of populating the matrix. The scores of both rows and columns are summed to give an indication of which design activities are key to the process (i.e. knowledge intensive), and critical problem areas for designers (i.e. critical information needed to design the product).

Transformation of problems to questions (N)

Using the problems a series of new questions based on this designer input/knowledge can be developed that structures the information required in the design process in an informal hierarchy. The highest rated problems are considered compulsory and are critical to the problem solving activity in the design process. Those problems rated less than a threshold value are considered optional but 'good-to-have' and can be submitted if available. In order to pose suitable questions from these problems, knowledge of the products, process, and design activities gained participating in the design process is required.

Implementation to a suitable medium

A medium for the transfer of the information developed from the questions above needs to be produced. Key media considered here are the World Wide Web or paper based depending on the technology available. The medium should be organised according to the levels of analysis described above. The compulsory questions required should be set out first, followed by the optional questions.

5.3 KNOWLEDGE REQUIREMENTS OF CUTTING TOOL DESIGNERS

In this section the results from the approach above are demonstrated. Learning and identifying the key activities in the design process have been elucidated in the previous sections. The results of the study are summarised in table 5.1.

5.3.1 Categorisation by novice

Fifty proposal forms were selected at random from the engineering files at Widia Valenite covering proposals submitted over the period 1998-2000. Thirty-five out of fifty forms are incomplete, but do have a remark sketch or component drawing attached to them.

Table 5.1: The breakdown of the study: mapping sales product views to the problems faced by the designers.

Sales	Design Type	Design Activities	Problems
S1 Produce Past Product (Low Design Involvement) **S2 Produce Variant Product** (Average Design Involvement **S3 Produce New Product** (High Design Involvement)	**T1** Reissue existing tooling **T2** Adaptation of competitors product to Widia tooling **T3** Modification to Widia Standard Tooling **T4** Modification to Widia Special Tooling **T5** Special configuration based on Standard Tooling **T6** Innovative design for the Company (New concept of cutting)	**Actual Design Process in cutting tool design at Widia** **D1** Create design department documents **D2** Identify key problem areas for design *Layout of component* *Need existing tooling drawings* *Need for a component drawing* *What are the design features?* *Is the sketch a suggestion or what the customer wants* *Need existing tooling drawings* **D3** Search for similar past designs *Drawings that are only kept in US or Germany* *Hard to trace Widia part numbers* *New drawing or modification to existing tooling* **D4** Assessment of cutting tool process parameters **D5** Prepare layout drawing **D6** Examine different configurations **D7** Perform necessary calculations *Horse Power* *Overhang ratios* *Forces* *Mechanics of tooling* *Geometry* **D8** Formalisation of concept design **D9** Assessment of technical & economic parameters *(Can it be made, will the customer buy it)* **D10** Prepare proposal drawing **D11** Prepare approval drawing **D12** Prepare detail drawing **D13** Collate relevant documentation for manufacture **D14** Checking/verification of detail design **D15** Modify design to changes highlighted	***Component*** **P1** Dimensions of component? **P2** Need for a component drawing **P3** Component Material **P4** Clearances **P5** Tolerances **P6** Restrictions **P7** Balancing of tools **P8** How much stock is available **P9** Surface finish ***Tooling*** **P10** What has the competitor done better? **P11** Quantities required **P12** Tooling Material **P13** Dimensions of tool required **P14** Style of insert **P15** Speeds **P16** Feeds **P17** Present tooling **P18** Adjustment? **P19** Mounting **P20** Complexity of forms **P21** Orientation of tooling **P22** Length of bar ***Process*** **P23** What is the process that the tool will undertake? **P24** Machine information **P25** Application of designed tools **P26** Coolant available **P27** Roughing or finishing **P28** Is required cutting time achievable? **P29** Swarf removal **P30** Don't know how to m/c ***General*** Customer Code No. Salesman To Salesman To customer Submission date Due date ***Customer*** Customer Address Quantities: Steel Quantities: Carbide How much are they willing to pay?

It is likely that for a simple enquiry that this would be adequate for a designer to design the required cutting tool but for a more complex tool, the knowledge requirements would be higher. A categorisation of how the sales engineer would perceive this design complexity was developed. The simplest level of proposal request is for a pure copy of existing tooling requiring no modifications only changes in orientation. In subsequent levels, modifications are made with some parts remaining standard until a level is reached where to the tooling to be designed is considered to be an innovation. The initial categorisation is shown in table 5.2.

Table 5.2 - categorisation of proposal requests.

Complexity of the task a proposal is asking from a designer

Level of complexity	Description of design task
1 (Copy)	No modification on either part only change in orientation
2	Modification on one item + other one standard
3	2 Modifications + one standard
4	Innovation in any item + no change or modification to others
5 (Innovation)	2 innovations (major modifications)

The fifty forms were sorted according to this categorisation and then the forms were shown in their respective categories to the two Salespersons participating in the study. This verified the categorisation by using expert opinion on the selection of forms. The verification results are discussed in the next section.

5.3.2 Verification by Salespersons

The Salespersons are not worried too much about complexity of the product, as they know the capabilities of the design team. The complexity issue is a design consideration, made by the designer on receiving the proposal. However, an important consideration for the Salesperson is the level of design involvement that the proposal will require from the designer. Design lead-time is the key consideration here i.e. when is the customer likely to see the product. Therefore, a Salesperson would in fact only identify three levels of product design as follows:

- Produce Past Product – low design involvement
- Produce Variant Product – average design involvement
- Produce New Product – high design involvement

These three bullet points above are shown in table 5.1, 1st column. One now has a sales view of the design process. Furthermore, the Salespersons upon consideration of the categories in table 5.2, suggest that even with a copy there is going to be modification of a standard Widia tooling. Copying an existing tool does not mean it is going to be a pure copy, but rather the same tooling with slight modifications made to it. From a sales perspective, designers will always try to modify a standard tooling set unless it is uneconomical to do so. Then special tooling is required and this is where the design task begins to get more complex. Sales engineers insist that even at the high end of the scale, say 5, the design itself may not be complex but involve many complex design issues. You cannot prescribe how many modifications are going to be made on any component or at any level. They go onto to suggest a more Widia friendly classification as shown in table 5.1, 2nd column. The next section describes these changes.

Change to categorisation

It was recognised through the interaction with the Salespersons that the initial categorisation was inadequate and did not reflect the views of the experts. Therefore, using the three levels of product design highlighted by the Salespersons, a basis for a new categorisation was considered. The problem here was to associate the types of design that were carried out by the designer to these levels. These were based on complexity of the product modifications that are required to produce the product. The product design level 'Produce Variant Product' relates to the design types T3 to T5 as shown in column two in table 5.1 because these are the types some level of verification occurs in the types of tool produced. Design types T1 & T2 are of past products or copying a competitor's product, which does not require much involvement of design. T6 is where design involvement is high requiring a great deal of design effort. The final design types are shown in table 5.1. The original fifty proposal forms were rearranged into the five categories identified in table 5.1, 2nd column. The next section describes the identification of requirement of design activities to achieve the design type; a novice and an expert perform this analysis.

5.3.3 Corresponding design types to design activities

If the design type 'Modification to Widia Special Tooling' (design type T4 in table 5.1) is required on table 5.3, then both the expert and novice should identify which of the design activities (3rd column in table 5.1) are required to design that product. For example the design type 'Modification to Widia special tooling' (design type T4 in table 5.1) requires at some stage in the design process the activity 'Assessment of cutting tool parameters' (design activity D4 in table 5.1). The designer is required to assess the environment that the cutting tool is required to operate in. This should be carried out for each design type assigning the corresponding design activities that are required by that design type in order for the product to be designed. The score on the left hand column of table 5.3 is a summation of the X's and R's across the row. For example there are 8 X's and 10 R's in row T2 of table 5.3.

It is interesting to note that both the novice (author (X)) and the expert (R) have similar scorings where each design type would require the designer to perform many of the activities in the design process. The only slight discrepancy is the assessment of the expert highlighting D4 (Assessment of cutting tool parameters) for design types T2, T3 & T4. This can be qualified by the difference in experience levels between the two individuals.

Table 5.3: Matrix to describe the relationship between design involvement & design activities.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	Score
T1	XR															1(1)
T2	XR	XR		R					R	XR	XR	XR	XR	XR	XR	8(10)
T3	XR	XR		R				XR	XR	XR	XR	XR	XR	XR	XR	10(11)
T4	XR	XR		R	R		R	XR	XR	XR	XR	XR	XR	XR	XR	10(13)
T5	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	15(15)
T6	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	XR	15(15)

The next section illustrates in which design activity (3rd column, table 5.1) the design problems are considered and what level of impact this problem will make on the design activity.

5.3.4 Design activities to Identified problems

Figure 5.4 shows an example of the mapping of design activities to design problems. Both the author and experts completed the matrix shown in figure 5.4. Deciding upon whether a problem has a high, medium or low impact on the design activities is based on individual's perception of the design activity and what is involved in the problem selection. A detailed examination of the actual design activities in cutting tool design and all 15 are shown in table 5.1. This matrix illustrates that the key activities (score >20) in the design process are: D4, D5, D7, D11 & D12 and D14 & 15. In these activities the impact of not having the information would cause most problems where the key design decisions are made. D4 and D7 are indicated on figure 5.4 the horizontal rings.

Design problems (Information required)

Legend:
High Impact=5
Medium Impact=3
Low Impact=3

Design Activities	Component: P1	P2	P3	P4	P5	P6	P7	P8	P9	Tooling: P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22									Score	
D1																															0	D1
D2	M	L	L		L				L	L				L	L	L	M														13	D2
D3																	M														3	D3
D4	M	H	M		L	M	L	L	L			M	L	L	M	M		L	M	L	L	L	H	L	M	L	L	M	M		53	D4
D5	H	H		M	M	M		M					H	M	L	L		L	L	L	M	L									39	D5
D6																															0	D6
D7	H		M	M	M		M	L	M			M		H	H	H		M	M	M		M		M				M			57	D7
D8														M						M											6	D8
D9										M	M	M	H										M	L							18	D9
D10		L											M	M				M	M		M										16	D10
D11	H	M	M	M	M	M	L	L	M				L	M				L	L		L	L				L			L		35	D11
D12	H	M	M	M	M	M	L	L	L				M	L				L	L		L	L	L	L	L	L			L		36	D12
D13																															0	D13
D14	L	L	L	L	L	L	L	L	L			L	L	L	L	L		L	L		L	L	L	L	L	L	L	L	L		25	D14
D15	L	L	L	L	L	L	L	L	L			L	L	L	L	L		L	L		L	L	L	L	L	L	L	L	L		25	D15
	28	20	15	14	16	14	8	9	11	4	3	11	20	22	12	12	6	12	14	8	11	9	11	8	7	5	3	8	7	0		

Figure 5.4: Matrix to relate design activities to design problems

Reading along the rows in figure 5.4 it is possible to evaluate the critical design activities in the design process i.e. where the value of the cutting tool expert is added to the process. In this case there are two areas where this can be seen, rows D4 & D7, which is where the designer would assess the cutting tool, process parameters (D4) and perform the necessary calculations (D7). These are the highest values in the score column with 53 and 57 respectively. Similarly the same can be achieved for the problems. The scoring system indicates the importance of the problems on the design process and hence gives an indication of the types of question that need to be asked of the salesperson when they fill in the new form. The type of design (a copy of a competitor's product or an innovative design) denotes what problems will be used as questions in the mandatory fields in the development of a web-based proposal form. The latter of the two types of design would require the most information about the component, tooling or process.

5.3.5 Transforming problems into questions

Essentially this is the knowledge provision to the designers and transforming problems faced by the designers (what they need to know or would like to know) to associated questions. It requires knowledge of cutting tool design, past designs and the processes that cutting tools can achieve. Table 5.1 illustrates that problems P1 (Missing dimensions of the component), P2 (Component drawing required), P13 (What are the dimensions of tool required) & P14 (What style of insert) are the critical problems (i.e. >20) that a designer faces when assessing a proposal. These could be considered as mandatory fields in the proposal form. With problems P1 & P2 it is obvious that these relate to the component to be machined; and the author developed questions based on the information required by a designer for the component:

- *What are the critical dimensions of the component?*
- *Can you supply a component drawing?*

These are common requests by a designer. For example; when designing a cutting tool, the designer will layout the component to scale on the CAD screen and evaluate the alternative tools that can achieve the required geometry of the finished component. Furthermore, questions relating to problems P13 & P14 are arrived at by a similar method. For example: P13 – Style of Insert (*Question – what style of insert is required?*) is a common problem; with multi-variable geometry, process and material combinations it is difficult to narrow down the solutions in the design search space. Here the designer is looking for a preference for a certain type of insert (by the customer) or a starting place to search for the nearest match. Thus it would be helpful if the salesperson can provide some guidance to aid the designer. The next section categorises the required knowledge of cutting tool designers.

5.3.6 Categorising the required knowledge

The required knowledge is categorised according to the type of knowledge identified in figure 5.1 the (initial categorisation model), section 5.1.3 of this chapter. This is presented in figure 5.5. It addresses the knowledge requirements of the cutting tool designer. By answering the questions proposed for each area, an element of the required knowledge is obtained.

The author categorised each individual term by examining what category the individual questions pertained too for example, "What process is the tool to undertake? I.e. roughing/finishing" is a manufacturing type of consideration, thus it was placed in the 'manufacturing possibilities category'. In another example "What are the design features?" is a question that is raised during the design process when designing the cutting tool and pertains to the method of design, hence its placing in the 'design methods' category.

The categories are interdependent, knowledge from one-category impacts on another frequently. Thus the knowledge requirements within the special purpose cutting tool design domain are difficult to capture and represent for future reuse. This section has identified the knowledge requirements of cutting tool designers at the preliminary design stage and has categorised the questions that designers have with the proposal information provided by salespersons. The next section discusses the benefits of using this approach in the analysis of the design process.

5.3.7 Validation of results

The validation of the knowledge required is undertaken in chapter six. The knowledge captured in this chapter will form the basis for the terms within the function, behaviour & structure models used for the ontology-based framework. The framework is a set of hierarchies that incorporated the knowledge obtained in this chapter. In chapter six the validation requires the users to rate the terms that form the ontology.

5.4 BENEFITS OF THE APPROACH

5.4.1 Generic benefits

The level of complexity of the design process and the product to be designed is also a factor in the applicability of the approach to the study of preliminary stages of a design environment. In a larger, more complex design environment, such as the design of aircraft the difficulty arises of managing the matrices with the considerations for an aircraft that has many millions of parts; whereas in cutting tool design, typically the average number of components can amount to anywhere between three to twelve components depending on the application of the tool. There are differences in the amount of information that is required for the examples given. In a group situation where there are multiple experts: combining the opinions of the experts will pose a problem. It requires time and effort for this process to be undertaken, requiring co-operation by the individuals in the process.

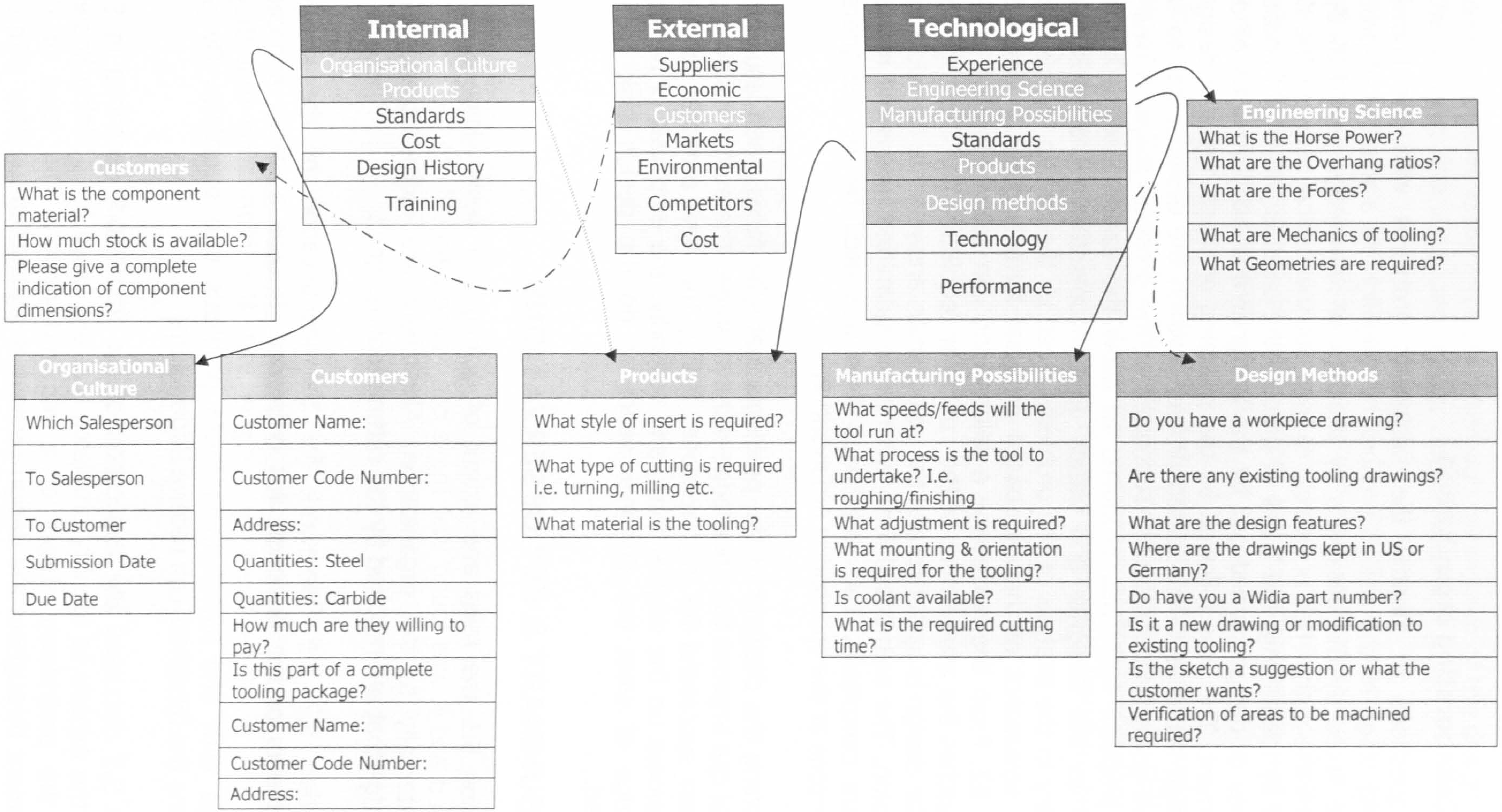

Figure 5.5: Categorisation of required knowledge.

5.4.2 Collaborating organisation

Using questions to identify the designer's problems with the knowledge gathering stage of the design process has highlighted a number of problems that are faced by the designers by the lack of knowledge provided. By this approach the author has been able to map out this critical stage of the design process by identifying; the types of product the salesperson would encounter, the types of design carried out by the designer and hence a level of design involvement. This was followed by the mapping of these 'types-of-design' via the design activities to associated problems which the designer has to satisfy from the goals and constraints submitted at the proposal stage. A new web-based proposal form was produced to allow the salesperson to submit an enquiry to the designer and attach any documentation that was deemed necessary in the analysis of the problems faced by the cutting tool designer. A sample screenshot of the web-based proposal form is given in Appendix B, section B2. From the homepage a salesperson can select the type of design that matches the assessment of the customer requirements. The page for the particular design is uploaded and the salesperson answers the questions before submission. The web-based form will not be submitted unless the mandatory fields are completed. This web-based form was used by the designers and salespersons at the sponsoring organisation.

Questioning the designer of the problems that s/he faces when issued with a proposal can improve the knowledge-retrieval stage. The author believes that it has been successful for two reasons: firstly, the new proposal form is an improvement on the original form, and secondly, the emphasis of putting the knowledge of what the designer needs to do the design task has been identified.

5.5 SUMMARY & KEY OBSERVATIONS

In section 5.1 the roles and extent of cutting tool design knowledge were examined and it was found that these can reside internally to the organisation and externally to the organisation. Also there are technological types of knowledge that are required by the cutting tool designer.

In section 5.2 the framework for the identification of the knowledge requirements of the designer was presented. It uses a matrix approach to identify the problems faced by designer with the information that they are provided with and transforming these problems into questions. By asking questions the designers can receive information.

Section 5.3 discussed the application of the framework described in 5.2. It allows the experts to identify problems that are faced in obtaining knowledge about the preliminary stages of a required design. The level of design involvement throughout the design process is highlighted together with critical knowledge intensive tasks through a thorough breakdown of the design process and the activities that a designer/expert undertakes.

Section 5.4 discusses the usefulness of the results obtained. It allows the design process to be quantitatively assessed by the organisation in order to gain value or cost of the actual design, and importantly to the salesperson in contact with the customer, it allows he or she to gauge the design lead time i.e. when will the customer get their design.

The following chapter builds on the work of this chapter by developing an ontology-based framework for the representation of special purpose cutting tool design. The knowledge required by the designers at the preliminary design stage is analysed and used to describe designs in terms of function, behaviour and structure.

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CHAPTER SIX

Developing an ontology-based framework for cutting tool design knowledge representation

6.0 INTRODUCTION

The analysis of the proposal stage identifies the knowledge and information requirements provision as a knowledge intensive task. When the designer receives a proposal, there is an information transfer between the salesperson and designer. The designer then begins his/her problem solving during which s/he considers many alternatives for the design of a cutting tool based on the information provided. However, the proposal stage for cutting tool design lacks any formal structure as indicated by the analysis in the previous two chapters. This has ramifications throughout the design process. It poses problems for effective reuse and understanding of the design information and knowledge provided. Providing a structured representation of this information is therefore critical.

This chapter focuses on the development of a formalised structure for the information and knowledge obtained at the preliminary design stage. Initially the information and knowledge is examined to identify function, behaviour and structure terms from the data of cutting tool design in chapters four and five. A functional ontology method is then used from research into Knowledge Systemisation to model the cutting tool system. The cutting tool system combines the cutting tool with the work-piece in one system. The ontology-based framework consists of four layers: system component, base- & meta-functions, sub-functions and design considerations. The chapter presents an ontology-based framework for cutting tool design knowledge representation. The framework is then validated and refined through case studies and questionnaires.

This chapter is structured as follows. In section 6.1 the requirements for the development of an ontology-based framework for cutting tool design representation are outlined. Section 6.2 introduces the considerations that are taken during the design process and describes an initial function, behaviour and structure model. Evolution to the ontology-based framework is described in section 6.3, including a functional decomposition of the systems components, identification of the sub-functions and the construction of the design considerations. In section 6.4 the framework validation is described, and finally, in section 6.5 the chapter concludes with key observations and a summary.

6.1 REQUIREMENTS FOR A CUTTING TOOL DESIGN KNOWLEDGE REPRESENTATION

During the author's participation in the sponsoring company it was observed that during design work it would have been useful to have an aide memoir while designing, to help when a decision was needed to solve a problem with a particular design task. In design reuse situations the need was different, it would have been helpful to have a structured set of notes that described the components of the cutting tool and why those components were chosen over others in such an option-rich domain. During many informal discussions with designers, and salespersons a similar view was echoed.

The problem however is that in an information rich and knowledge intensive domains what are the critical 'need-to-know' items and how does one proceed to organise such items of knowledge and information? The answer lies in providing a structured framework that represents this knowledge and information. But first an understanding of what is the process that brings about this knowledge and information is required.

The cutting tool designer considers many trade-offs before a tool can be designed. The information provided by the salesperson is understood by the designer (trying to make sense of the new cutting tool), then a historical design similar to the target is found and the considerations made as to what is mapped to from the historical design to the target. These considerations lack a formal structure for cutting tool design. As a result it is difficult to select a design for reuse and to understand the designs found. It was highlighted in the literature that an ontology-based framework for representing design information would be a satisfactory method of reusing and understanding the design information better. For this research ontology can be described as:

> *"A structured set of concepts with attributes together with the relationships between the concepts to describe a domain".*

An ontology-based representation requires that certain criteria be met in order for it to be of practical use in the cutting tool design domain. In a competitive environment it is necessary that this representation is usable for customer orientated design tasks. In this sense the representation must provide the knowledge in an acceptable manner so that it can be used without any doubt as to its consistency. Also that the representation be based on a solid grasp of both theory and practice and to its coverage of different knowledge types in the domain. In meeting these criteria a practical framework is developed which could be used for practical problems in cutting tool design. The next section discusses the development of the initial framework. It describes the development of the terms and concepts that are used as the framework evolves.

6.2 DEVELOPING AN ONTOLOGY-BASED FRAMEWORK

The development of the ontology-based framework began with the identification of a set of language terms that were used in everyday cutting tool design, extracted from an analysis of the proposal stage of the cutting tool design process. Within this language there were terms for what the cutting tool was supposed to do (proposal form and design concepts), what it was doing while cutting (feedback from the customer) and what it looked like (the design drawings). Also amongst this language there were other types of knowledge the reasons why the cutting tools were designed in a particular way.

The categories highlighted in table 5.1 require several considerations to be made regarding the design of the cutting tool. The 'questions to be answered' in column 3 of table 5.1 within chapter five highlights the design considerations that have to be made when designing a special purpose-cutting tool. Essentially they give answers to the question: how is the cutting tool going to be designed? It is these 'hows' that form the basis for this ontological commitment.

The questions in table 5.1 can be decomposed into several concepts, which have attributes that need to be completed when performing a design task. The relationships between concepts can be seen at a higher level or 'functional level' of the ontology. However, to provide a decomposition of the cutting tool design domain a method to model the concepts, attributes and relationships was needed. It has been observed by the author that a common method for design domain decomposition was by function, behaviour and structure. The next section describes the terms function, behaviour and structure for cutting tool design.

6.2.1 Understanding Function-Behaviour-Structure (FBS) for cutting tool design

The purpose of this section is to describe what is meant by function, behaviour and structure in cutting tool design. It is recognised that these are difficult terms to define the descriptions given below offer practical use of the terms.

Interpretation of structure

Structure in cutting tool design can be defined as the components and characteristics of those components that constitute the artefact. For example, typical components of a cutting tool are the insert and the toolholder. The insert can be characterised by the angle at which it sits on the toolholder, and the toolholder can be characterised by assigning a type of toolholder.

For this research the structure of cutting tools can be described as the components depicted on design drawings produced by the design department. Analysing the designs for their structural elements requires the user to be able to understand the drawings. The components include a toolholder, clamping system and insert. The arrangement of these components is an important consideration in describing the structure of the cutting tool. This may include the geometry, dimensions of the tool and critical areas of the tool to be considered.

Interpretation of behaviour

Behaviour is the manner in which the artefact acts under specific conditions i.e. what does the cutting tool structure defined from above exhibit when it cuts the workpiece. Factors such as tool-wear, chip formation, heat generation and metal removal rate are examples of exhibited behaviour of a cutting tool. Different insert/component material combinations will exhibit different behaviours. The tool described in design case one is a good example where the different structure would exhibit different cutting conditions. Figure 4.2 (chapter four, section 4.5.2) shows the initial design, which incorporates a rhomboid insert whereas figure 4.3 (chapter four, section 4.5.2) also shows the final design in which the insert has been replaced by a triangular insert. This was due to the former insert not being able to remove the material completely and thus the insert/material combination in this case would not behave as required. The tools are basically the same and perform the same function but a subtle change in structure affects the behaviour so that the goals and constraints could be met.

Interpretation of function

This is what the artefact performs. In the case of cutting tools the definitive high-level function is to 'remove material' or to 'define form' of a component. However, these are overall system functions for the complete cutting tool and thus we have to consider the functions of each of the components individually. Taking each component of the cutting tool system (described in the following sections) and examining what its functions are within the whole system and how the functions relate to each other to achieve the higher level overall system function mentioned above. The next section discussed the identification of function, behaviour and structure for cutting tool design.

6.2.2 Initial function, behaviour & structure for cutting tool design

For the initial function-behaviour-structure model multiple views were incorporated. The model is based on theory and practice in machining. This practice of cutting tool design was learned by the author through participation in the design process described in chapter four and five. Also the development of the author's knowledge of the theory of metal cutting was obtained through a video lecture series (Chattopadyay, 1997), relevant industry-based literature (Sandvik Coromant, 1994) and academic literature (Bhattacharyya, 1984; Schneider, 2002).

However, because of the model being an interpretation of the author's view a certain amount of bias could creep in, therefore further views from the cutting tool experts (25 years experience a piece) and a non-industry related novice (with several years experience of cutting tools) were incorporated by a three-hour workshop. The author explained the principles of function-behaviour-structure to the participants of the workshop together with examples of each element with respect to cutting tool design. The participants were then asked to brainstorm their opinions of function, behaviour and structure in cutting tool design. The responses given were recorded from the 'post-it' notes and can be found in appendix C1.

Figure 6.1 depicts the initial function-behaviour-structure model developed as a representation for cutting tool design knowledge involving both commercial and design knowledge. A customer gives a set of goals and constraints that need to be achieved by the design. The designer has to match a set of functions that will achieve these goals and constraints. To achieve these functions the design must behave in a certain way based on a given structure. From another point of view, we can obtain a structure of the cutting tool i.e. a design recognising the features of the cutting tool on the design as the structural elements of the design. Then we can look at the relationships between these structure elements and the behaviour required to achieve this function.

Using the author's experiential data collected from participation and the data obtained from the workshops the terms for function, behaviour and structure were extracted. Due to the amount of data that was gathered during the previous stages of the research it was felt that an advantageous method of viewing this data would be in the form of a matrix to highlight the relationships between the functions, behaviours and structures. The initial function, behaviour and structure model is shown in figure 6.1. A qualitative assessment by the author followed in deciding upon the locations of the data within figure 6.1. In the design literature (Pahl & Beitz, 1984; Gero, 1990; Rosenman & Gero, 1999) it recognised that function is achieved by behaviour and that behaviour is exhibited by structure. Approaching the values in the matrix from the structure angle: a structure will exhibit behaviour and that behaviour will affect the function of the designed artefact. Forming the obtained data into these characteristics is not an easy task. The terms in the matrix were identified on this basis by the author using post it notes and writing down one function, behaviour and structure term on a post-it that could be obtained from the data. Appendix C2 shows the complete list of terms used for the initial FBS matrix. Table 6.1 presents examples of where the terms were obtained for function, behaviour and structure. The three terms are related as shown in figure 6.1.

Behaviour

Function	Chip Formation	Heat Generation	Metal Removal Rate	Swarf Control	Tool Wear	Surface Finish	Produce Required Dimensions	Power Consumption	Vibration	Speeds & Feeds	Cutting Temperature	Cutting Time	Cutting Forces	Torque	Cutting Velocity	Comparison with competitor	Competitive advantage	Cost	Technically viable	Technologically acceptable	Economically viable	Increase revenue	Environmentally viable
Remove Material	X	X	X	X	X																		
Define Form			X		X	X	X	X		X		X	X		X			X	X		X		
Cost Effective			X		X	X	X	X		X	X	X			X		X	X	X	X	X	X	X
Cutting Tool Solution			X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Quality					X	X	X					X				X	X	X	X	X	X	X	
Time			X		X		X	X		X					X			X	X		X		

Structure	Chip Formation	Heat Generation	Metal Removal Rate	Swarf Control	Tool Wear	Surface Finish	Produce Required Dimensions	Power Consumption	Vibration	Speeds & Feeds	Cutting Temperature	Cutting Time	Cutting Forces	Torque	Cutting Velocity	Comparison with competitor	Competitive advantage	Cost	Technically viable	Technologically acceptable	Economically viable	Increase revenue	Environmentally viable
Cutting Envelope			X				X									X	X		X	X			X
Depth of Cut		X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X			
Type of Toolholder	X		X	X		X	X									X	X		X		X	X	
Type of Insert	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	
Pocket																		X	X				
Length of Cutter						X	X		X				X	X					X				
Tolerances			X			X	X		X	X	X	X	X	X	X				X				
Clearances			X				X		X	X									X				
Cutting Angles		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X				
Clamping Mechanisms													X	X		X			X				
Chip Gash	X		X	X															X				
Orientation			X						X	X									X				
Type of Tool		X	X	X		X	X	X				X	X	X	X	X	X		X		X	X	
Component	X		X	X	X	X	X	X		X	X	X	X	X	X				X	X	X		
Application/Process	X		X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X		X
Number of Inserts		X	X		X	X	X	X	X	X	X	X	X	X	X		X		X	X	X	X	
Materials		X	X		X	X	X	X	X	X	X	X	X	X	X				X	X	X		X
Calculations					X		X												X	X			
Chip Breaker	X																		X				
Shim Seat																			X	X		X	
Coatings		X	X		X	X				X	X								X	X	X	X	

Figure 6.1: Initial FBS model.

Structural elements were also directly read-off a set of ten randomly selected designs. These require knowledge of the designs as learnt by the author during the activities described in chapter four. For instance, Cutting Envelope is the space required for the cutting tool to perform its task without fouling (making contact) with the component or the machine that it is placed on.

Table 6.1: Examples of points of reference for function, behaviour & structure.

Term	Point of Reference
Function Remove Material	Obtained from the novice in the above-mentioned workshop. Also the industry and academic related literature suggests that the ultimate goal for the metal cutting industry is to "remove metal". A corresponding behaviour described below will achieve this removal at a certain rate.
Behaviour Metal Removal Rate	Obtained from the industry and academic literature and video during the development of cutting tool theory by the author, and also the workshop from both the experts and novice. This term will have consequences on the components selected for the cutting tool and hence a certain structure will be exhibited. This behaviour will also affect the function of the cutting tool.
Structure Type of Insert	Obtained from the table 5.1 in chapter five and also in the industry and academic the literature. Also it is possible to identify the insert type on the designs themselves. It is a consideration that the designer takes into account, as the type of insert will exhibit certain behaviour.

How do we read this matrix?

The matrix is read by identifying a function of the cutting tool and then reading across the matrix and observing the behaviours that are achieved by the cutting tool exhibiting those functions denoted by an 'x' in the matrix cells. Each of the behaviours exhibits certain structural elements by reading vertically down the matrix. This illustrates the relationships that occur between the various terms in the cutting tool industry. Starting from the structural end is just a reversal of the above process. Using the example given in table 6.1, if the function 'Remove Material' is selected then following the ex's the function is achieved by considering *chip formation, heat generation, metal removal rate*, swarf control & *tool wear*. Taking one of these behaviours as an example (Metal Removal Rate) and reading down the matrix the structure will exhibit the following characteristics: *cutting envelope, depth of cut, type of tool holder, type of insert, tolerances, clearances, cutting angles, chip gash, orientation* & *type of tool.*

Need for a more detailed model

The question to be answered for the design representation was could a design (a proposal form, component drawings and a final design) be presented fully using the terms that were identified in figure 6.1. The author used the functional, behavioural and structural terms in figure 6.1 to map to ten randomly selected designs to see if the terms could represent a design. However, from the study it was apparent that not all the terms could be mapped. This was most noticeable within the functions. Upon closer inspection it was obvious that the functions were too broadly defined and also they did not take into account the component and cutting tool as a system. This initial function, behaviour and structure model provided a thorough understanding of function, behaviour and structure but a more detailed approach to developing an ontology-based framework with function, behaviour and structure was required. The next section shows the evolution from this initial FBS model through to a FBS ontology-based framework.

6.3 EVOLUTION TO THE ONTOLOGY-BASED FRAMEWORK

This section describes the evolution of the Function, Behaviour and Structure model into an ontology-based framework for cutting tool design. The model was influenced by the methodology described for Knowledge Systemisation (Kitamura & Mizoguchi, 2002; Mizoguchi & Kitamura, 2000; Kitamura & Mizoguchi, 1998). The work of the aforementioned authors and the components of the methodology used in this research are described in section 6.3.1. The process of deriving functions is described in section 6.3.2, followed by the description of the generation of the design considerations or 'how's' in section 6.3.3. The generic form of the design ontology is then finally described in section 6.3.4.

6.3.1 Knowledge systemisation

Mizoguchi & Kitamura (2000) describe the foundations of knowledge systemisation. Knowledge systemisation is the development of vocabularies/concepts in terms of how people describe phenomena, theories and target things under consideration. Their approach is to use ontological engineering to build knowledge with a computer-interpretable vocabulary with terms that can describe knowledge systematically. Their method develops a vocabulary for reuse for implementation on a system using Function Behaviour Representation Language (FBRL). Their methodology for the decomposition of a design domain using function as a first class category in design knowledge organisation is the influence for the decomposition of the cutting tool design domain described below. Their work primarily identifies functions for mechanical systems. The next section describes the cutting tool system considered for this research.

The cutting tool system

In this research the mechanical system is the 'cutting tool system', defined as the cutting tool and the workpiece as described in table 1.1, within section 1.3.3 of chapter one. Applying this definition of the system and assessing what changes occur both from practical and theoretical perspective to the components leads to the development of a set of base-functions as described in the next section.

Change of state for identifying base-functions

The method Mizoguchi & Kitamura applied to mechanical systems was particularly interesting as the other method for developing function behaviour structure design schemas were concentrated around systems with energy flows such as power plants. The energy would flow from component to component and be changed depending on what the component was designed to do but still there would be a differential across the component. In a mechanical component system such as a cutting tool system there are no such energy flows. And modelling in this respect is therefore a difficult task having to relate how individual component within the system interacts with each other.

Even in a mechanical system the components will undergo a state change, but it may be difficult to see the change because the system is different once it has performed a task. In cutting tool design, there are changes of state to the cutting tool itself and the work-piece. The work-piece's change of state is far easier to picture as it has undergone a transformation from a raw material state to a finished state. For the cutting tool the insert will have exhibited a change from its initial state, a common problem in the machining industry is insert wear. The insert would wear from its initial cut of the component, thus along with the change in the work-piece the cutting tool itself would have changed. The components of the cutting tool that are not in contact with the machined work-piece will also undergo micro changes. For example the tool holder and clamping system will experience forces created during the cutting process, therefore from their initial states they change albeit a very small amount. The following section presents the functional decomposition of the components within the cutting tool system. The ontology-based framework development process is depicted in figure 6.2

6.3.2 Assigning functional concepts

This section describes the process of assigning base-functions for the toolholder, insert, clamping system, and work-piece. By considering the 'changes of state' that each component will experience as the cutting tool performs its designed task on the workpiece the functions can be derived. These are according to Kitamura & Mizoguchi (2002) 'base-functions'. Additionally there is a further category of functions known as 'meta-functions' as described in the next two sections.

Domain analysis

The values for behaviour and structure in figure 6.1 are a contribution of the research and form the knowledge capture activities defined in chapters four and five. In chapter four the author identified the types of knowledge in the special purpose cutting tool design domain and developed a methodology to capture this knowledge – chapter five of this thesis. The terms that are found in figure 6.1 were captured during the proposal stage investigation of the design process. The terms in figure 6.1 are the interpretation of the author and are therefore subject to bias. To overcome this, the author and an expert from the domain verified the terms in figure 6.1 through informal discussion. The ontology-based framework is a continuation from this process with the terms from figure 6.1.

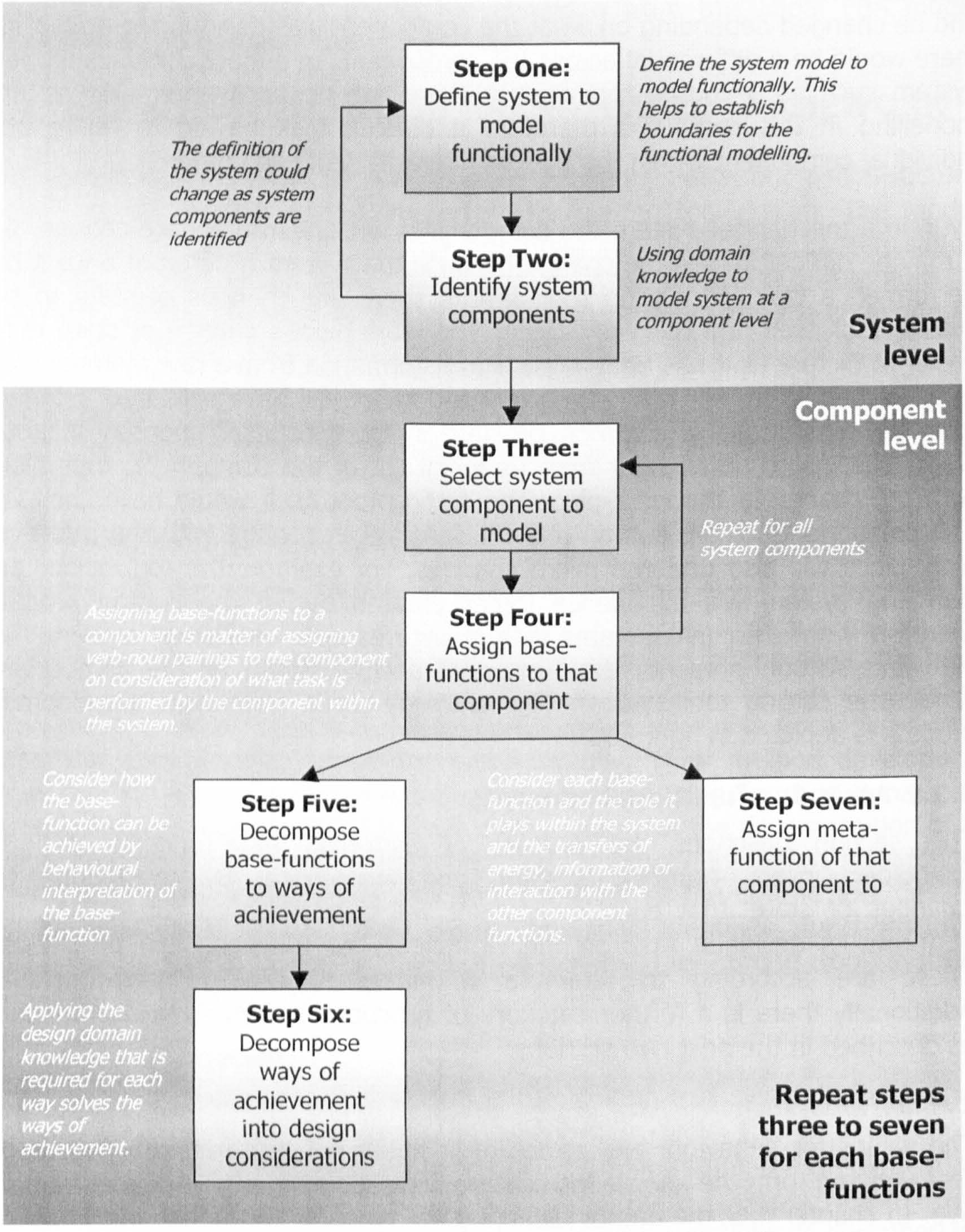


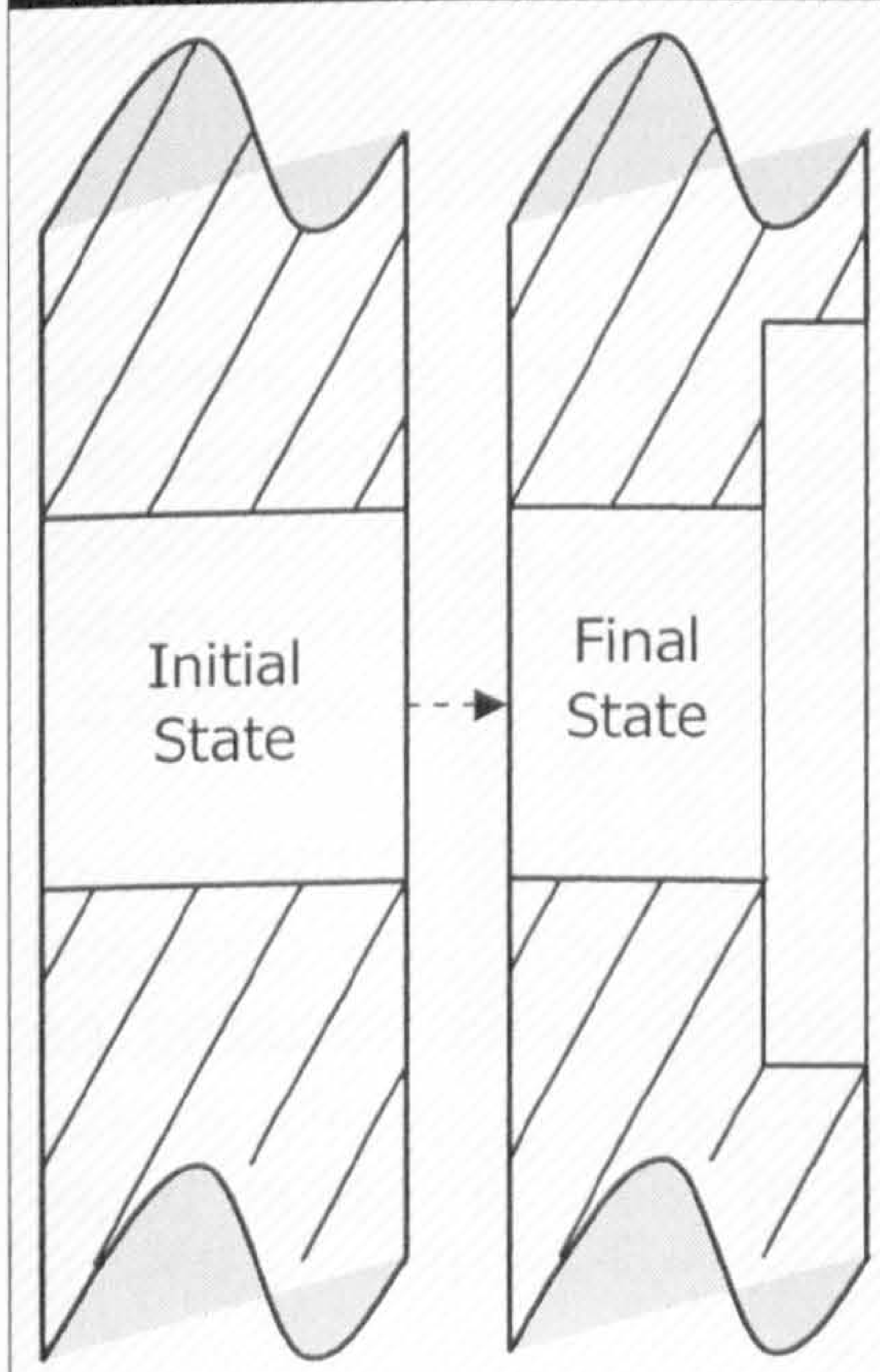
Figure 6.2: The ontology-based framework development process.

Throughout the iterative process of generating the base-functions, meta-functions and ways of achieving hierarchies the experts have been close to the process verifying the items through informal discussion. For example, through this iteration the base-functions were reduced to ten from an original set of 14 base-functions. But after discussions with various domain experts it was noted that the verb-noun combinations were either repeated or were not valid descriptions of the function of the component. An example of how the base-functions were derived for each component is illustrated in table 6.2.

In this example, section 1 shows the diagrammatic representation of the change in state of the workpiece by machining a bore into the right hand face. Thus, there has been a dimensional change from d_1 to d_2. Also there is now an increase in cost from C_1 to C_2 of the workpiece. This is because the workpiece in its raw material form (initial state) has little value. The value of the workpiece increases if work is carried out on it i.e. the bore in the final state.

Table 6.2: An example of obtaining the base-functions for the workpiece.

Section 1: Behavioural model of work-piece



Section 2: Changes of parameter behaviour values
Heat Generation (T_1, T_2) Surface Finish (S_{f1}, S_{f2}) Change in Dimension (d_1, d_2) Increase in Cost (C_1, C_2)

Section 3: Functional Interpretation of behaviour values		
Functional Mapping	*Functional Interpretation*	*Functional Concept*
o-focus p-focus	Heat Generation ((T_1), (T_2))	"Remove Heat"
o-focus p-focus	Surface Finish ((S_{f1}), (S_{f2}))	"Attain Quality"
o-focus p-focus	Changes in Dimension ((d_1), (d_2))	"Remove Metal"
o-focus p-focus	Increase in Cost ((C_1), (C_2))	"Value Addition"

In section 2 of table 6.2, these are the behaviours that change when undergoing the task with the cutting tool. In section 3 of table 6.2 the parameter behaviour values are functionally interpreted. The functional mapping denotes 'o-focus' and 'p-focus': object focused and port focused functional interpretation respectively. The behaviour of a cutting tool system component in interpreted functionally by identifying at the component's (object) functional contribution within the cutting tool system. Whereas, with 'p-focus' the interaction of this functional contribution by the component to it's neighbouring concepts is considered. For example, heat generation would undergo a temperature change from T_1 to T_2 this would be transferred to the insert. Functionally this can be represented as "heat generation" for 'o-focus' and $((T_1), (T_2))$ for 'p-focus'. The final column of section 3 provides the functional concept that will be considered as the base function by considering what's happening functionally by interpreting that behaviour. All components of the cutting tool system were considered in the same manner to generate their functional concepts. Figure 6.3 shows the final set of base-functions used in the latter part of the work.

Base-functions for cutting tool design

A base-function is the interpretation of behaviour under a given goal. The term is given to discriminate from the meta-function (Kitamura & Mizoguchi, 2002). A meta-function is a conceptualisation of type of a base-function and interdependency between them. While a base-function is concerned with the change of objects in the domain, meta-function is concerned with base-functions (Kitamura & Mizoguchi, 2002). Analysing the cutting tool system mentioned above it was possible to identify 10 base-functions presented in figure 6.3. Also the meta-functions are given for each base-function i.e. how each function affects another in appendix C section C4.

Meta-functions for cutting tool design

There are several meta-functions defined by other authors are available (Keuneke, 1991; Mizoguchi & Kitamura, 2001). A meta-function enhances the functional representation by providing additional distinctions about functions, that is, by specifying types of functions (Keuneke, 1991). The following meta-functions described are used in this thesis including reasons for their selection:

ToEnhance: This meta-function provides an enhancement to the role of a base-function to another base-function. For example, the clamping system provides further restriction to the toolholder when focusing on the 'holds insert' base function. Also, the attaining of quality in the workpiece provides an enhancement to the increase in value base-function. The value of the workpiece increases when the quality is attained.

ToProvide: When a base-function generates the materials which another base-function intentionally processes, the base-function is said to provide material for the second base-function. The produce shape base-function provides generates the increase in value of the workpiece.

ToControl: The regulation of the behaviour by one base-function in relation to another base-function. For example the reduce tool-life will affect the level of quality attained on the workpiece. A reduction in tool-life will decrease the quality of the workpiece surface finish.

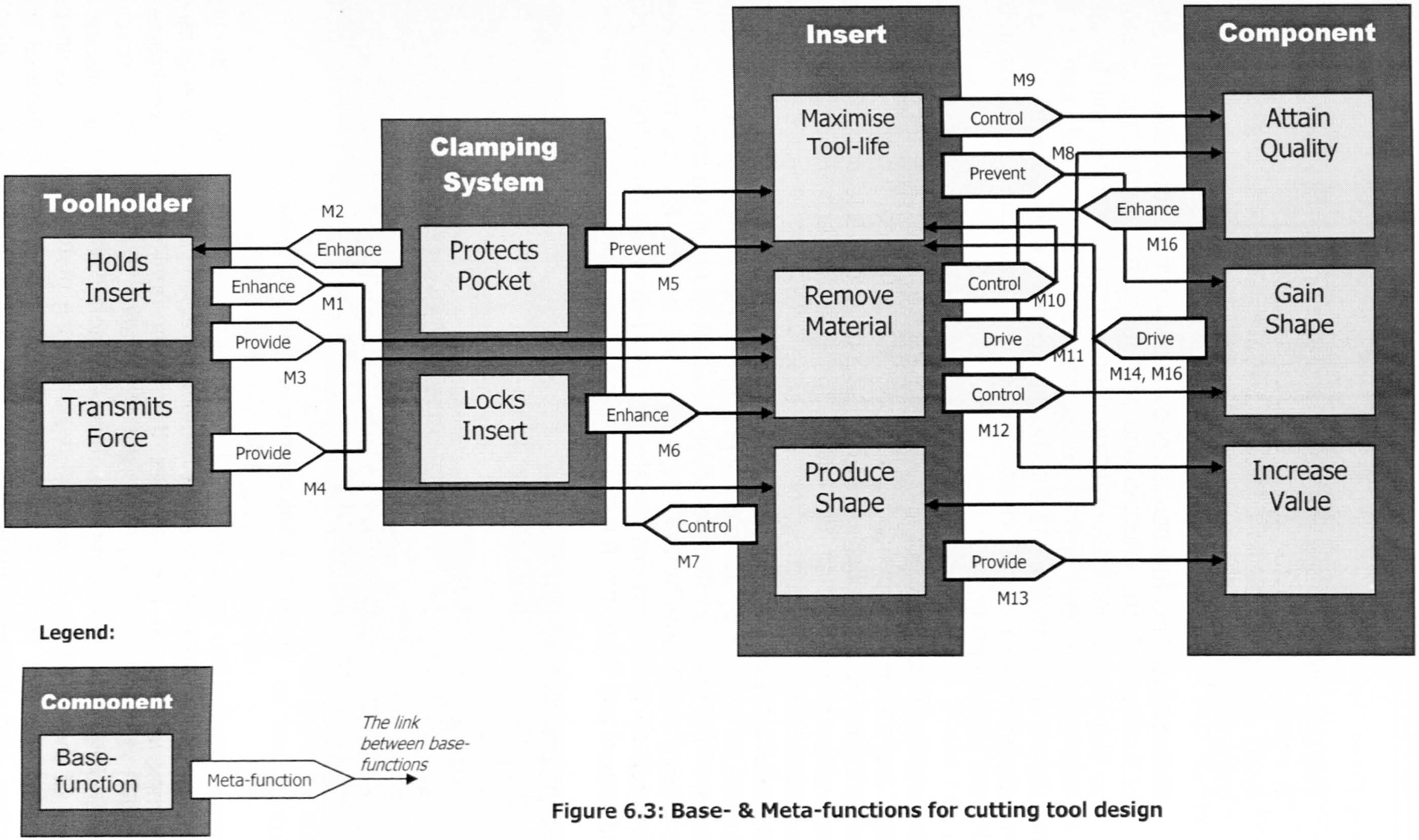


Figure 6.3: Base- & Meta-functions for cutting tool design

ToDrive: When a base-function generates or transfers such energy that is intentionally consumed by another function. Remove material by the insert drives the attain quality in the workpiece. The workpiece utilises the energy transfer from the insert to the workpiece.

ToPrevent: This function is concerned with the undesirable side effects of functions. If the effect of one base-function is detrimental to another so that the second base-function cannot be achieved it is said to have a "ToPrevent" meta-function. For cutting tool design, a reduction in tool-life will not allow the shape to be gained in the workpiece. In cutting tool design the aim of the designer would be to reduce the 'reduction in tool-life' base-function.

The meta-functions used for this ontology-based framework for cutting tool design are shown in appendix C section C4. Each meta-function affects the base-functions in a number of ways. Essentially the selection of the meta-functions is by considering the interaction that the base-functions of each component within the cutting tool will have with each other. Based on this qualitative assessment an appropriate meta-function can be selected. With reference to figure 6.3, the component 'insert' has the base-function 'remove material'. This base-function has been designated the meta-functions 'control' and 'enable' which affect other functions of the system. Also the base-function is affected by base-functions donated by meta-functions from the toolholder: 'holds insert' and 'transmits force'. This sub-system is presented in figure 6.4.

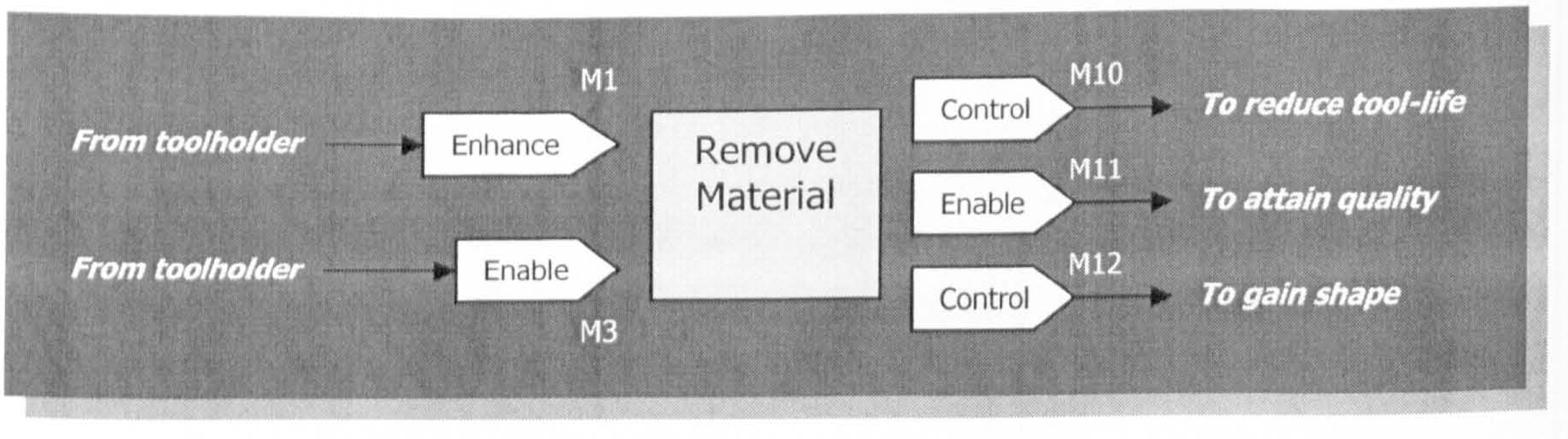


Figure 6.4: The remove material sub-system.

Remove material can be considered to 'control' the reduction in life of the insert when the correct selection of insert is made in relation to the material to be cut. The remove material also enables the attain quality of the workpiece by providing a surface finish and the size and shape of the workpiece. Furthermore, the remove material base-function controls the gaining of the shape of the workpiece because in removing the material the size & shape is produced and the depth of cut is controlled by the remove material base-function. The meta-functions that provide interaction from the toolholder component are enhance and enable. That is, the toolholder base-function 'holds insert' enhances the remove material base-function and hence enhances the function of the insert wihin the system by providing the support to the insert. The toolholder also enables the insert to produce the shape on the workpiece by positioning the insert in the correct place. Each of the base-functions was then decomposed into the ways of achieving those individual base-functions as presented in the next section.

6.3.3 Functional hierarchy

This section focuses on the domain knowledge for cutting tool design. The construction of the functional hierarchy is realised by identifying the 'ways of achievement' followed by the design considerations. Each function can be solved by a set of sub-functions known as 'ways of achievement'. For instance the hierarchy shown in figure 6.5 (one of ten hierarchies) shows the base-function 'remove material' from the set of functions defined for the insert in figure 6.3. *'Chip Formation Way', 'Required Finish Way'* and *'Desired Shape or Size Way'* are sub-functions for remove material. Below each of these sub-functions are the design considerations the designer must take into account when addressing a design solution that requires any of the sub-functions fired by the proposal to be solved. The design considerations are the attributes that provide answers to the sub-functions and are constructed from the behaviours and structures that were developed in the initial function-behaviour-structure model in section 6.1. There are nine further hierarchies that complete the cutting tool design ontology. They can be found in appendix C6, figure C1 to C9.

The ways of achievement and subsequent design considerations (defined in appendix C, section C7) are organised into a hierarchy with the design considerations being the lowest level of the functional hierarchy. This domain knowledge structure is static as it represents facts about the domain without provision for how this knowledge maybe used in problem solving. It represents the considerations the designer must make in order to carry out a design task.

Description of the function remove material

This section illustrates the use of a part of the functional hierarchy for cutting tool design shown in figure 6.5. This represents one of ten functional hierarchies that are defined in appendix C6, figures C1 to C9.

Ways of achievement

Chip formation way: In metal cutting the method of removing material is by the forming of chips. Chips are formed when the inserts comes into contact with the work-piece.

Required finish way: In practical cutting tool design three types of surface finish can be obtained or are often utilised by the cutting tool designer. It is important to know that there are different combinations of insert/work-piece combinations that can affect the surface finish of the product.

Desired Shape or Size Way: A major part of the designers work is to fit a cutting tool to the shape and size of the work-piece to be machined. Knowing the component features, materials and dimensions are critical characteristics that a designer should be aware of. The cutting tool design described in figure of chapter four is a good example.

Design Considerations

Forces: The forces required to remove the material from the work-piece. Especially important if the cutting tool is of length that might induce bending when cutting. In milling applications this can be necessary if the power of the machine is in doubt.

Depth of Cut: What amount of material is going to be removed from the work-piece? This consideration will have bearing on all the other considerations here.

Tool Wear: Cutting tool life is probably one of the most important economic considerations in the tooling industry. As the material removal takes place, the insert will wear, that is, there will be some degradation of the surface of the insert, which will eventually lead to dimensional inaccuracies in the work-piece. Adequate consideration must be made to the tool wear by considering the material/geometry combinations of the cutting tool.

Plastic Deformation: Due to the high pressure at the point of contact between the insert and the work-piece the material will deform. This will have an affect on the chip formed and subsequently the effect the removal of the material.

Geometry of Cutting Tool: The geometry of the insert is of primary concern here. Different cuts can be obtained by choosing different geometries of insert. Also the angles that are formed when the insert is placed on the toolholder will have to be considered to produce the required cut.

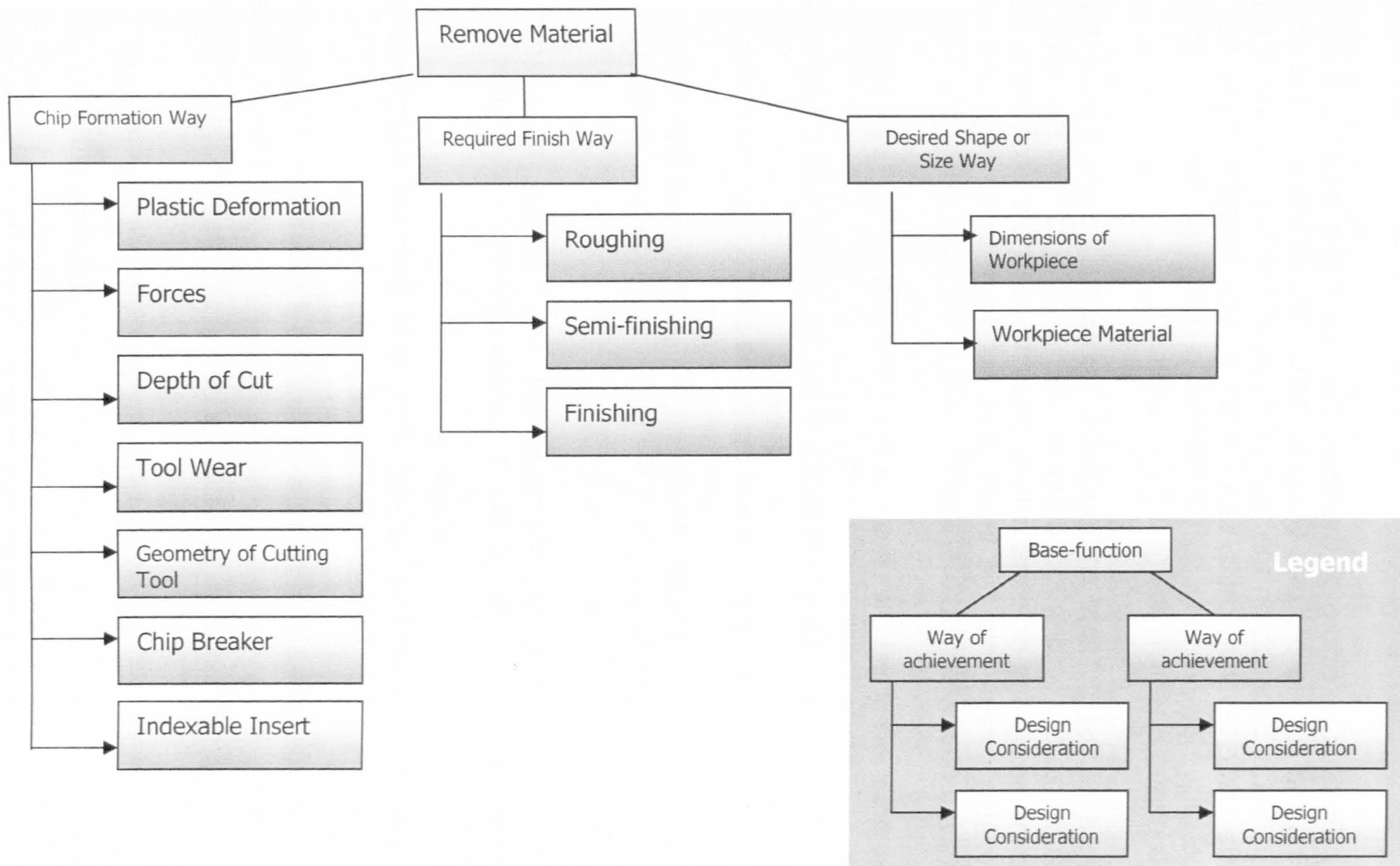


Figure 6.5: Functional hierarchy for 'remove material'.

Chip Breaker: A feature on the insert that aids in the breaking of the chip during the cutting process. Generally these are all ready on the chosen insert but it depends on the type of material that is to be cut. If it is a brittle material that chips easily then a chip breaker might not be necessary. However, if a ductile material is machined then the chips can be continuous which require the chip breaker.

Indexable Insert: There are four basic shapes and several special shapes available to the cutting tool designer, each having its own strengths and weaknesses giving different cutting characteristics and economics. Being indexable means that the insert does not have to be reground when worn but merely turned to a fresh cutting edge and used again.

Roughing: will affect the choice of the insert and tooling geometries.

Semi-finishing: will affect the choice of the insert and tooling geometries.

Finishing: will affect the choice of the insert and tooling geometries.

Dimensions of Work-piece Feature: This will influence the size of the cutting tool to be employed and the number of inserts to be used on the cutting tool.

Geometry of Work-piece Feature: This will influence the size of the cutting tool to be employed and the number of inserts to be used on the cutting tool.

Work-piece Material: The material of the work-piece will affect the choice of the insert and tooling geometries.

This section has described the functional hierarchy for cutting tool design. The section describes structure of the design considerations needed to be made to complete a design task. The next section will describe the generic ontology-based framework for cutting tool design.

6.3.4 Generic Ontology-based framework for cutting tool design

In the previous two sections the basis for the ontology-based framework for cutting tool design knowledge has been presented. This section ties both of the above areas together and describes the generic ontology-based framework for special purpose cutting tool design including the component, base-functions, meta-functions, and ways of achievement and design considerations for the task of cutting tool design.

Functional structure understanding

The functional understanding task that has been undertaken in the sections 6.3.1 to 6.3.4 illustrates the development of a set of concepts that can be used to form a functional concept ontology. This method is based on the work of several authors (Kitamura & Mizoguchi, 2002; Kitamura et al, 2000; Mizoguchi & Kitamura, 2000). Their method identifies functional structures of an artefact from its structural and behavioural models. They propose a method, which has been followed to achieve the research reported in this chapter. The work develops a functional concept ontology built upon an extended device ontology, which is presented in figure 6.6.

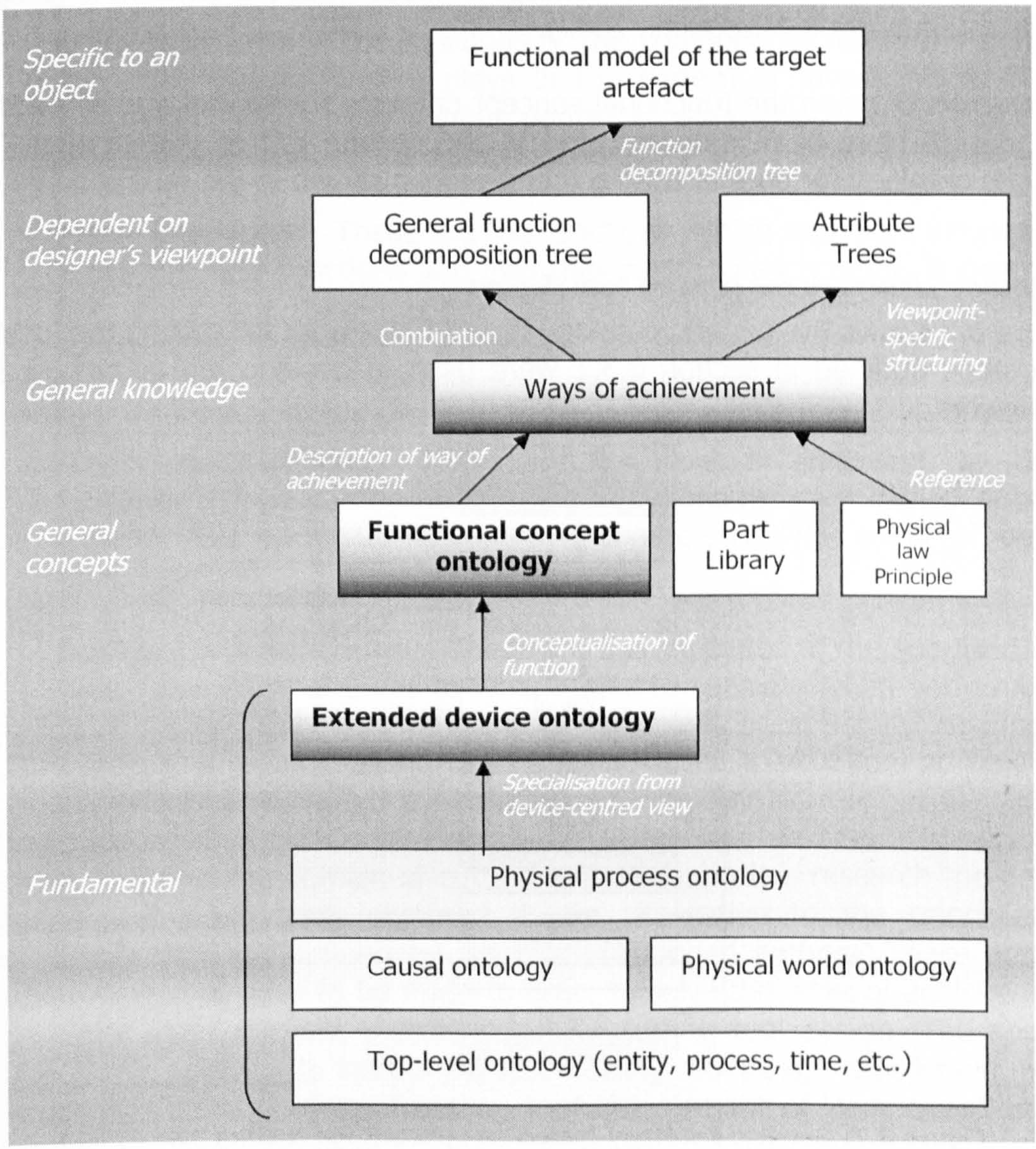


Figure 6.6: Hierarchy of ontology and knowledge according to Kitamura & Mizoguchi (2002).

This is a hierarchy of ontology and knowledge. Knowledge in a certain layer is described in terms of the concepts in the lower layer. The five fundamental layers of the ontology are the collective substrates on which consistent knowledge can be built in layers. The two areas of interest for this research are the functional concept ontology and the ways of achievement layer. Functional concept ontology specifies functional concepts as an instance of function defined in device ontology. The definitions scarcely depend on the device, the domain or the way of its implementation so that they are very general and usable in a wide range of areas (Kitamura & Mizoguchi, 2002). Way of functional achievement is knowledge about *how* (in what way) a function is achieved, whereas the functional concept is about *what* the function is going to achieve (Kitamura & Mizoguchi, 2002).

The results of using the functional concept ontology for special purpose cutting tool design have been demonstrated in the section 6.3 of this chapter. The generic ontology for special cutting tool design is shown in the next section.

Ontology structure for cutting tool design

Figure 6.7 shows the generic ontology-based framework for cutting tool design. The steps outlined in section 6.3.1 were used to develop the ontology-based framework.

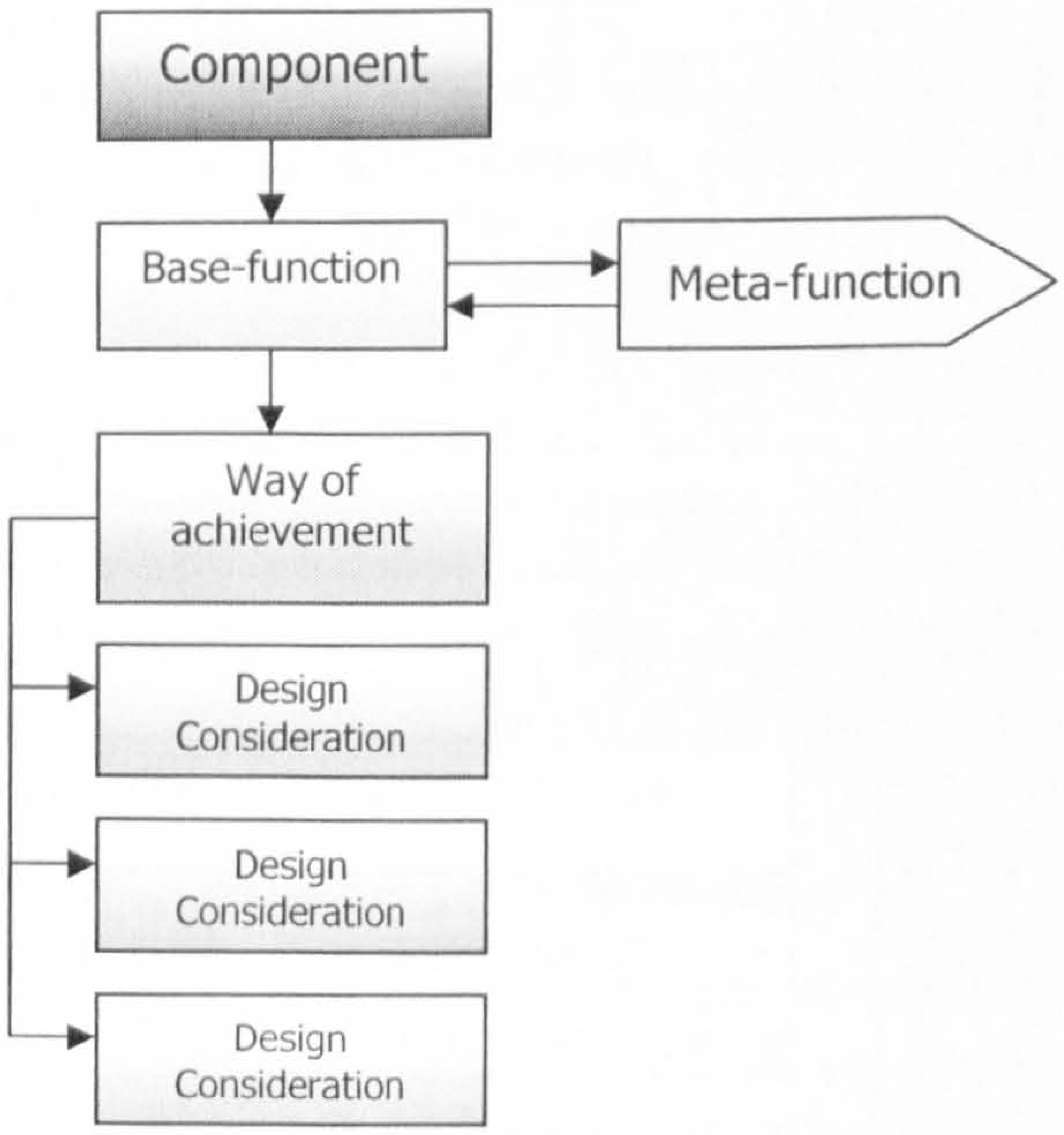


Figure 6.7: Generic ontology-based framework for cutting tool design.

The design ontology can be described on four layers: the component, the base- & meta-functions, the ways of achievement, and the design considerations. This work provides an extension to the work of Kitamura & Mizoguchi to reflect the features of the captured knowledge in the special purpose cutting tool design domain. The ontology is generic to the design of special purpose cutting tools.

Component – An element of the mechanical system under consideration. Each component within the system will perform a function that is necessary for the function of the whole system. The level of decomposition to descend to depends on the system and is dependent on the area of interest for the functional decomposition. For cutting tool design it was necessary to decompose to the lowest level of component, as these were the areas in which designers made most considerations.

Base-functions – The functions of the components within the system. The roles the component plays in the system of investigation. These represent what the component performs within the system; these are related by considering the meta-functions.

Meta-functions – These are the functions, which represent information about the base-functions and how they relate to each other. It describes the effect one base-function has on another function. The meta-functions are presented in appendix C section C4.

Ways of achievement – The link between the base-functions and the design considerations. These are the ways of achieving the base-functions. There can be multiple sub-functions for each individual base-function and each sub-function will characterised by a set of design considerations.

Design considerations – These are the attributes of the sub-functions, which give information as to what issues to consider when performing a design task. They can be either behavioural or structural relating to which way a component will perform under a situation or how the component or system is constructed respectively.

In order to reflect the domain of cutting tool design in this research the design considerations have been captured as an alternative to the principles of achievement that are defined by the aforementioned authors. These are the considerations that need to be made in order to solve the ways of achievement, which were more relevant a description for cutting tool design. The specific nature of this ontology to special purpose cutting tool design is reflected in the inclusion within the ontology framework of the element of 'component' in the functional analysis. The representation of the form of the generic ontology for special purpose cutting tool design thus reflects this addition to the Kitamura & Mizoguchi from the depiction of their ontology hierarchy.

A viewpoint selection from this generic ontology is required, as not all the design considerations will be taken into account when designing, as all the information may not be presented at the time of the proposal. This ontology gives a complete picture of the special purpose cutting tool design practice. A viewpoint of the ontology is selecting the appropriate ways of achievement and design considerations for the task at hand. The next chapter shows the selection of a viewpoint of the ontology for cutting tool design reuse.

This section has described the development of an ontology-based framework for special purpose cutting tool design knowledge representation by a method of functional structure understanding. The framework is now validated in a two-stage process: an assessment of the functional terms in the ontology and by applying the ontology through a number of case studies to ascertain its suitability as a framework to represent special purpose cutting tool design knowledge.

6.4 VALIDATION OF THE ONTOLOGY-BASED FRAMEWORK

The previous section has described the development of the ontology-based framework for representing cutting tool design. This section describes the validation of the framework, and in particular it discusses the validity and completeness of the ontology-based framework. The purpose of the validation is to show that the framework represents special purpose cutting tool design knowledge. In the next section the approach taken to test the framework is described. Section 6.4.2 illustrates the case studies used to test the framework. The validation process is described in section 6.4.3, followed by an analysis of the results from the tests in section 6.4.4.

6.4.1 The approach

The first phase of this validation process was to allow the participants to rate the terms of the ontology-based framework for completeness: whether the ontology is complete to describe a special purpose cutting tool system.

The decision to use a questionnaire was to find the views of the users in a replicable manner. The questionnaire scale would remain the same for each user and provide a comparable quantitative assessment of the ontological terms provided. It allowed the author to gain an insight as to how the user perceived the ontological terms allowing them to fill out the questionnaire themselves which the author believes to be important as the users have control over the process and provide as honest answers as possible.

The framework was assessed by questionnaire composed of closed questions in which the participants were required to rate on a scale from 1 to 6, strongly disagree to strongly agree. The questionnaire was split into four sections:

assessing the components within the cutting tool system, the base-functions, the meta-functions and the ways of achievement. An example of a question from part of the questionnaire for the cutting tool system is presented in figure 6.8. The participants were asked to rate the addition of the toolholder in the cutting tool system.

For the 'ways of achievement' the participants were required to assess the ways presented to them. In each the participant looked through the design considerations for the way and then rated the completeness of the way using the questionnaire rating scale. This closed question approach allows a structured approach to the analysis of the data but can also confine the response of the expert but in each question the participants were also encouraged to give another example if deemed necessary. A sample questionnaire can be found in appendix C, section C9.

Please indicate on a scale 1 – 6 the degree to which you agree with the component of the cutting tool system.

Scale: 1 indicates that you strongly disagree with the concept proposed, and 6 indicate that you strongly agree with the concept proposed.

Note: **If you disagree with one of the following please indicate by writing below the box what you would prefer instead.**

Toolholder

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Figure 6.8: An example of question.

For the second phase of the validation process three case studies are presented in tabular form. Case one is presented in table 6.4 and 6.7. In table 6.7 there are three columns; the first shows the ontology element i.e. the selected route through the ontology to provide information about the case study. The middle column, describes the values that are attributed to the respective ontological element in column one. Finally column three provides description as to why the values were chosen in the middle column. The table represents the knowledge within cutting tool design and it is validated against five measurement criteria developed from the requirements for a knowledge representation and ontology design. The criteria used below are desirable features of a representation of knowledge (Darlington, 2000). When one chooses to represent something in an ontology one is making design decisions. To guide and evaluate one's designs, one needs objective criteria (Gruber, 1993). A common ontology defines the vocabulary with which queries and assertions are exchanged among agents and need only describe a vocabulary for talking about a domain. Ontological commitments are agreements to use the shared vocabulary in a coherent and consistent manner. The author used a combination of measurement criteria from existing literature on ontology development & design and knowledge based systems to derive the measurement criteria, which are described as follows:

- *Adequacy* – Measures the whether the special purpose cutting tool design knowledge representation describes a vocabulary for talking about special purpose cutting tool design. The need for this criterion is to test whether the framework can aid the communication between the various participants in the special purpose cutting tool design knowledge;

- *Coherence* – Measures whether the cutting tool design knowledge is represented in a logical and consistent manner. Whether a part of the ontology framework is selected to represent a design is logical and consistent with other parts of the framework and knowledge within special purpose cutting tool design;

- *Completeness* – Measures whether the framework represents all the aspects of the knowledge in special purpose cutting tool design. The special purpose cutting tool design ontology represents the vocabulary for all of the tools that are possible in the domain;

- *Soundness* – Measures whether the representation is based on reason. The ontology vocabulary gives information based on both practical and theoretical approaches providing sound advice for the users of the ontology;

- *Usefulness* – Measures the usefulness of the ontology and offers a conceptual foundation for a range of anticipated tasks. This criterion was selected to demonstrate that the ontology-based framework be used practically in a variety of applications of special purpose cutting tool design.

These criteria are used to form a questionnaire to validate the framework represented by the tables. A sample questionnaire can be found in appendix C, section C10. Three expert designers validated the framework over a period of two days, the profiles of the participants is given in table 6.3.

Table 6.3: Profiles of participants in validation process.

	Experience (Years)	Roles during period of experience	Educational Background
User One	30	Tool user, Tool detail designer, Gauge Designer & Detailer	Higher National Diploma, Mechanical Engineering
User Two	25	Cutting Tool Design & Sales	Graduate Level, BSc Mechanical Engineering Design
User Three	28	Cutting Tool Design	Higher National Diploma, Mechanical Engineering

An informal discussion was tape recorded and later transcribed to support the validation process undertaken. The following section describes the design problems used and their development into cases studies for the validation process.

6.4.2 Case Studies that model cutting tool design

The previous section described how the validation of the knowledge framework was to be carried out. This entails the use of case studies as a test of applying the framework with domain knowledge. There are three case studies to test the framework; each case study describes common design task knowledge that is generic to special purpose cutting tool design. These case studies reflect the kind of design task carried out on a day-to-day basis by the sponsoring company.

The case studies illustrate the application of the framework by representing the information provided in design documentation for three design cases (proposal form, workpiece drawing & design) according to the ontology structure. For the validation process three design problems were chosen from the author's design work during the first six months of his participation in the design process and developed into case studies for the validation. The first two are mentioned in chapter 4 during the development of the knowledge elicitation phase of this research. The third case study was taken from the work of the MSc research student carried out in conjunction with this research (see Hodges, 2002). The cases are described in the following sections.

The author constructed each case from the proposal form and relevant final design work. First a consideration was made as to what was required in the design i.e. the design task required an analysis of either the insert or toolholder or both. Based upon the decision here a function was selected from figure 6.3 (see section 6.3.2) for the component to be designed e.g. selecting 'Reduce Tool-Life' from the component 'Insert' or 'Attain Quality' from the component 'Workpiece'. For this exercise it was felt that the selection of one insert would be sufficient to test the framework as the knowledge would become too great to handle. Therefore it is recommended that only one function per component be selected in any design analysis depending on the design task.

Once the function is selected, a decision is required as to the sub-function that is to be used for the component selected. Referring to figure 6.5 of section 6.3.3 (there are nine others shown in appendix C, section C6), there are three choices: *chip formation, required finish* and *desired shape or size.* Each requires a certain piece of knowledge to be given. The knowledge is extracted from the documentation mentioned above by terms that fill the values for each of the chosen ontological element (sub-function hierarchy) and also the explanation for the inputted value is included. This is illustrated for Case Study One in table 6.4.

Case study one: T-Slot Milling Cutter

The aim of the task was to design an end mill for the component shown in figure 4.2 (chapter four, section 4.5.2), which required the machining of a 5mm pocket on the backside of the component. The motion of the proposed cutting tool is described in chapter four, section 4.5.2. The workpiece is made from Cast Iron. The customer has a machine mounting that requires a DIN1835 shank. The customer hasn't asked for a specific inset type. From the KEN transcript shown in table 4.1 the major areas of concern for the novice designer (the author) are given in table 6.4.

Table 6.4: Areas of concern for case study one: T-Slot Milling Cutter

Area of consideration	Description
Workpiece	The material Cast Iron will require coolant to be supplied affecting the size of the toolholder.
Insert	Due to the small size of the cutter insert selection will a challenge here. There two insert types that would be of use in this application: triangular and parallelogram. Both inserts should be placed on the design to see which will do the job best. Aim for the largest possible insert.
Toolholder	The size of the access area to the surface to be cut is a major consideration and will affect the size of the toolholder and hence the size of the insert that can be used.

For this case study (a similar process was applied to cases two and three) the author chose a base function for each of the components shown in table 6.4 to highlight the features of the design case. From figure 6.3, p123 for the workpiece in table 6.4 the author chose to model the workpiece by 'Gain Shape'. The criteria for this selection were that in the design specification the area that the tool is to operate in small and the region in which the tool has to make the cut is difficult to access. The 'Gain Shape' base-function accounts for the dimensions of the workpiece as a consideration in its ways of achievement. As this phase of the design is focusing on the workpiece the author chose the 'Workpiece' way of achievement. Having selected this way of achievement the author then consulted the design documentation to find the information that could be assigned to the design considerations. For example, the way of achievement 'Workpiece Shape & Size' the author studied the design specification and the final produced design and recorded that the tool would operate through a cylinder bore on the workpiece to reach the region for the removal of material. An explanation for this was given as shown in table 6.5. It is observed by the author that knowledge is required here to decide upon the consideration to focus on.

A similar approach was taken in the consideration for the insert in case one. As highlighted in table 6.4 the concern for the designer is the size of the insert to remove the material completely due to the size of the aperture in which the tool is to operate to produce the cut. Therefore, the author selected the base-function 'Produce Shape' from figure 6.3. The design case illustrates the design of a milling cutter and hence the selection of the 'Milling' way of achievement. Once again the author turned to the design documentation and extracted the values for each of these design considerations under the 'Milling' way of achievement. For example the material of the workpiece is given in this case on the design specification or proposal sheet. In another example the size of the coolant holes can be read of the design drawing for the finished cutting tool. The explanation for the respective design considerations were obtained by from the knowledge of the author through his participation in the design process during the undertaking of the milling cutter design. For example during the interaction described under the KEN approach demonstrated in section 4.5.1 for this design case, the author was able to explain why the physical strength of the cutter may be affected by the size of the coolant holes. This is shown in table 6.5 on p139.

As described in this case the toolholder is an important part of the design to consider because of the size of the access area to the cutting region and the sizing of the cooling holes on the toolholder itself. The author considered the 'Transmit Force' base-function and the 'Continuous Contact' way of achievement as the insert is supported by the toolholder continuously by the toolholder. To assign values to the design considerations the author once again used the design documentation and his own experience of the case in extracting the values. For example the pocket dimensions can be obtained from the cavity sheet. The cavity sheet represents a standard drawing within the organisation illustrating the specifications in order for the pocket to be manufactured on the toolholder. The size of the inserts can be found on the design drawings for the case.

Table 6.5: Case study one: T-Slot Milling Cutter.

Ontology Element	Description of Value	Explanation
Component	Workpiece	In this design consideration is given to the workpiece due to the narrow access area, thus the selection of a function from those on the workpiece.
Function	Gain Shape	The requirement for this design is to produce the shape on the back face of the bore, therefore choosing of the function 'gain shape'.
Way of achievement	Workpiece	Consideration is being given to the workpiece 'way of achievement'. If the centre of attention for this design was another attribute from the list of sub-functions under 'Gain Shape' then another would have been chosen.
Design Considerations		
Wrokpiece Material	Cast Iron	The material of the component being known is valuable for several reasons in cutting tool design. The selection of the appropriate type of insert and the speeds and feeds that the tool can be run at.
Cost	£140	Only relevant if the customer asks for a particular cost target but as none was given here then it is placed here for the sponsoring company's interest. For design reuse i.e. searching for designs it is probably not useful because this is a special and there would not be another like it.
Surface Finish	Good	In this case a good surface finish was required. This would affect the insert chosen and the number of passes made to achieve the depth of cut required.
Workpiece Shape & Size	A cylinder with a bore through (Space for the tool to pass through to the back face)	This is the cutting envelope size i.e. the space that the tool has to do its work in. The tool passes through the bore and machines a 5mm depth of cut to a diameter of 111mm from the centre of the workpiece bore.
Tool/Material Selection	Triangular coated Carbide insert/Steel toolholder with DIN 1835 shaft.	Most inserts used today in the cutting tool industry are of a coated carbide variety. In this case two potential inserts were investigated to achieve the appropriate cut on the workpiece, an I.C. 4.56mm parallelogram insert and an I.C. 6mm triangular insert.
Workpiece Name	Not given	In many cases the component name isn't given either in the proposal or design drawing from the information is being obtained.

Ontology Element	Description of Value	Explanation
Component	Insert	Special attention has been made to the selection of the insert to cut the face of this workpiece. Two inserts were compared in order to select the appropriate insert giving the correct cut to the workpiece.
Function	Produce Shape	The insert is producing a shape and is considered an important characteristic for this particular design.
Way of achievement	Milling	As this is a milling operation, the sub-function 'milling' has been chosen for this design example.
Design Considerations		
Speed	Not calculated	A qualitative assessment made that the speed is not excessive and is not given in the proposal form, as the salesperson does not see it as a major problem.
Feed	Not calculated	A qualitative assessment made, the feed is not excessive and is not given in the proposal form, as the salesperson does not see it as a major problem.
Workpiece Material	Cast Iron	Important to know the material of the workpiece as it provides guidance on how to set up the cutting tool in terms of insert selection, placement and cutting angles.
Rigidity	Not considered	The length of the tool is not of concern in terms of rigidity. Also the power requirements are not that high for this application as the material is Cast Iron.
Physical Strength of cutter	Size of the Coolant holes	For the small size of the cutter, the physical strength would not normally be an issue but in this case the addition of coolant holes. This is because it is cutting Cast Iron, the depth of cut is small and therefore the power requirement will be small so there will be great forces on the cutting tool. However, the addition of the coolant hole to a toolholder diameter of 14mm could pose a problem. A qualitative assessment is made that 4mm would suffice and the strength would be fine.
Cutting Tool Material	Carbide	The inserts used are made of coated carbide. Most inserts used today in the cutting tool industry are of a coated carbide variety.
Power Available	Not calculated for this application	Power is often not considered when designing a cutting tool unless the designer feels that the solution requires because of tool/material/speeds/federates could cause problems.
Surface Finish	Good	In this case a good surface finish was required. This would affect the insert chosen and the number of passes made to achieve the depth of cut required.

Ontology Element	Description of Value	Explanation
Component	Toolholder	A specific type of shaft is required on the toolholder. A DIN1835-B32 is required to fit the customer's machine. The toolholder design would be an important consideration in this design case.
Function	Transmit Force	The toolholder transmits the force to the insert so that the cut can be made, hence the choice of this function.
Way of achievement	Continuous Contact	This is continuous contact with the workpiece through the insert. It must transmit force throughout the cutting process.
Design Considerations		
Power Required	Not calculated for this application	Power is often not considered when designing a cutting tool unless the designer feels that the solution requires because of tool/material/speeds/federates could cause problems.
Number of Inserts	Four	This value is dependent on the style of the cutter. In this a T Slot cutter four inserts are required so that a cut is made on each 90-degree revolution of the cutting tool.
Speeds & Feed	Applicable to the customers requirements	This is not considered here as the speeds and feeds are not out of the ordinary i.e. not too high for the designed cutting tool. The cutting tool is fed through the bore with 1mm to spare at the inserts and then bought in place to affect the cut.
Locations of Inserts	90 degree	The cutting edge of the inserts are located at 16mm radii from the centre of the cutting tool and located at 90-degree angles through the rotation of the cut. Also the cutting edge is placed 4-degrees ahead of centre giving a positive cutting angle.
Pocket Dimensions	See cavity sheet	Usually in a detailed design the critical dimensions are given and the actual pocket machining parameters would be referred to a cavity sheet. A cavity sheet provides
Depth of Cut	5mm	This is the amount of material that has to be removed from the back face of the bore.
Size of Insert	I.C. 6mm triangular	Inserts are sized by dimension of the inscribed circle (I.C.). In this design case, two different inserts were chosen to see if they would do the job.

Case study two: E-Z Set Cutter

The aim here is to design the toolholder for the E-Z SET unit shown in figure 4.4, section 4.5.3 of chapter four. The E-Z SET unit is the feature of the drawing that contains the insert. This type of unit has a micro-adjustment, which is achieved through the application of a micrometer gauge contained within the unit. The feature of this design case as demonstrated by the work in chapter four is the use of calculations used in the special purpose cutting tool design domain. From the KEN transcript shown in table 4.3 the major areas of concern for the novice designer (the author) are given in table 6.6.

Table 6.6: Areas of concern for case study two: E-Z Set Cutter

Area of consideration	Description
Workpiece	The workpiece is increasing in value by the machining of the bore. We have to consider the size of bore to be machined and the surface finished required therefore consider the performance way of achievement.
Workpiece	The workpiece is chosen because the workpiece is gaining a shape. The workpiece requires a bore to be to be machined within it. The diameter of the bore will determine the size of the E-Z Set unit that can be used and also affect the size of the toolholder that can be designed. Hence the selection of design considerations based on the tool way of achievement.
Clamping Mechanism	The concentration of the design effort is around the E-Z Set unit, which contains the insert and the micro-adjustable unit. This is a clamping mechanism for the insert

Case study three: Special Grooving Cutter

This case requires the designer to consider the special groove on the workpiece and then consider the design of an insert to cut the groove plus a toolholder to hold the insert. The insert form would be formed onto standard insert by preparing a design of the required form given. The major considerations for this case are given in table 6.7. Appendix C section C8 presents the design and proposal form, workpiece drawing and design for case three, figures C10 & C11 respectively. The form to be cut can be seen in figure C10 as the area bound by the diameter dimensions 96.1mm, 110mm & 115mm.

Using these considerations the construction of table 6.5 for case one and the tables shown in appendix section C8 tables C1 and C2 for cases two and three respectively. Each case study shows which functions, sub-functions that were selected by considering criteria in the design proposal and associated designs for the areas of interest that have been highlighted in the summary tables in this section. The sub-functions are then instantiated with knowledge from the cutting tool design domain through the proposals and associated design.

Explanations are given to the selection of knowledge types used in each instantiated case. The next section describes the validation process.

Table 6.7: Areas of concern for case study three: special grooving cutter

Area of consideration	Description
Workpiece	The form has to be cut into the workpiece and therefore it gains a shape. The problem here is the small access are of the workpiece causes problems for the designer in restricting the size of insert possible to be selected and subsequently the toolholder. Also the form on the workpiece is unique and requires the development of a special form insert.
Insert	Due to the small access space within the workpiece the selection of the insert is of prime importance. Also the form to be formed onto the insert is small and this causes problems of breakage during cutting. The design consideration is to provide an economic tool-life. The workpiece material is steel.
Toolholder	The toolholder will have to be designed based on a standard toolholder and therefore the way of achievement for the base-function 'Holds Insert' considered is standard features.

6.4.3 Validation Process

The first stage of the validation process set out to see whether the ontology-based framework represents completely special purpose cutting tool design knowledge. The experts were given the base- and meta- function model shown in figure 6.3, the ways of achievement diagrams (see figure 6.5, & figures C1 to C9 in appendix C section C6) and a questionnaire. The author explained the features of each of the diagrams to the participants on an individual basis – the participants were then required to answer the questionnaire. For the ways of achievement the participants were required to examine the way and proceed down the hierarchies and assess whether design considerations are appropriate for the selected way.

The purpose of the second stage of the validation is to show that the framework represents special purpose cutting tool design knowledge by applying domain knowledge to the framework and assessing against the five criteria set. Three cutting tool design experts tested the model. The experts were given the three case studies (including the proposal form, workpiece drawing and the final design) and the framework tables (see table 6.5) that represented the information in the case studies. Along with these the experts were given a questionnaire (shown in appendix C10); each expert was required to examine the design case study and the framework table crosschecking whether the knowledge represented in the framework tables represents cutting tool design knowledge. Subsequently they were to assess the knowledge in the framework against the criteria in the questionnaire. Any changes that were required during informal discussion were recorded and later transcribed for use in the discussion of the results obtained from the questionnaire. The validation process lasted two days and the results are discussed in the next section.

6.4.4 Analysis of the results

This section discusses the results of the special purpose cutting tool design framework validation process with the feedback given by the three design experts for the two phases of the validation. By examining the documentation provided by the author the experts were able to test whether the ontology-based framework provided a complete representation of knowledge within special purpose cutting tool design.

Phase one

The results for the rating of the vocabulary of the ontology are summarised in table 6.8. For each user the individual ratings are averaged for the categories in table 6.8. Also an average is given across the three users to arrive at an overall opinion of the vocabulary of within the ontology. It is shown that the overall user ratings are positive. 'AVG' is an abbreviation for 'average'. The lowest score across the areas of the ontology are the base-functions and the ways of achievement with 5.3 and 5.5 (the maximum is 6) respectively. Observing the table in terms of the individual users the lowest value of 5.5 from the users one and three. With the rating scale used a value of '5' would indicate an 'agree' from the users and a '6' would indicate 'strongly agree'. It is interesting to note that both user one and user three have a similar educational background.

Table 6.8: Averaged ratings for the ontology-based vocabulary.

	Rating 1 – 6			
	User1	User2	User3	
Cutting tool system	6.0	6.0	5.8	5.9
Base-functions	5.3	5.4	5.2	5.3
Meta-functions	5.8	6.0	5.4	5.7
Ways of Achievement	5.0	6.0	5.5	5.5
	5.5	5.9	5.5	AVG

The base-functions have the lowest average rating of 5.3. Whilst this represents a positive rating of 'agree' from all the users (see above for description of rating scale). The problem area in this analysis of the vocabulary was two base-functions that were viewed negatively by two of the users.

Users two and three gave 'Protect pocket' ratings of 4 & 3 respectively, which with a qualitative view represents 'slightly agree' and 'slightly disagree'. This term 'protect pocket' was assigned to the clamping system (which included the shim seat, screw & clamp). Their disagreement with the use of this term was whether a function of the clamping system was to protect the insert pocket.

Both users did however concede that if the shim seat were incorporated into the clamping system sub-system then there would be a contribution to protect pocket. Their ratings still remained as there remained a significant doubt. The two users were unable to offer an alternative. Taking the view of user one (rating of 5) into consideration 'protect pocket' that the clamping mechanism stops the insert moving in harsh conditions of cutting. With the cutting forces an insert moving can damage the toolholder. This weak interpretation provided support to kept the base-function within the ontology framework until a better verb-noun contribution is made.

The second term to receive a negative view again by users two and three was 'reduce tool life'. Both users rated it as 2, which is 'disagree' on the rating scale. The discussions between each of the users and the author suggested that this was a technical problem with the definition for which they were assessing. The aim of the cutting tool industry is increase the tool life as this represents a more economic proposition. User two pointed out that in his opinion that

> *"...The aim of any tool design is to achieve maximum tool life, therefore 'reduce' should read 'maximise'."*

Putting this new term to the third user during the discussion with author after he had made his selection of 'disagree' the author found that user 3 agreed with this interpretation. This was adopted by the author and changed within the ontology: 'Reduce tool-life' becomes 'Maximise tool-life'. The author considered any further changes that would have to be made to the framework based on this change in the relationships of base-functions and meta-functions but found that the relationships still hold.

The second area of concern in the analysis of the results is the low average rating in the ways of achievement category. A large influence in this direction is the views of user one. His individual rating for ways of achievement was 5. Upon closer inspection user one's feedback for *firm support way, cutting force way, heating of component way, power requirement way, operation/process way* were given a rating of 4. Asked of his decision to rate these five 'ways' with 'slightly agree', the user replied: *"I personally would not use these ways for my design work,"* the author asked *"what 'ways' would you use?"* User one replies: *"I prefer the application focused ways, such as those for turning or milling."* It is noted that for these application based 'ways' (turning, milling, boring etc.) this user rated 6 throughout. It is difficult to change the framework based on one users own preference and thus the author cannot justify a change in the framework.

The interpretation of function is a problematic area especially the assigning the verb-noun terms to functions. This functional interpretation requires a common understanding of the domain to be achieved successfully. Overall impressions of the ontology-based framework for special purpose cutting tool design were positive. User two even commented that:

> *"...It (referring to the framework) is brilliant, it covers everything I can think of and even some additions that I would never have thought of."*

The feedback received from the users has been implemented and is presented in this thesis and the tables and figures of appendix C. Generally the users were happy with the domain vocabulary as it illustrated the terms used to talk to each other more explicitly. This is within a domain that retains the majority of its knowledge implicitly amongst it's more experienced participants making it difficult for both knowledge retention or a novice to find this need-to-know knowledge and information.

Phase two

The results for applying cases to the framework were analysed and are presented in table 6.9. Averages for individual user are given and the averages are given across the three users to arrive at an overall opinion.

Table 6.9: Analysis of results for the framework validation.

	Rating 1 - 6			
	User One	**User Two**	**User Three**	**Average**
Case Study One				
Adequacy	6	5	5	5.3
Coherence	5	6	6	5.7
Completeness	5	4	5	4.7
Soundness	6	6	5	5.7
Usefulness	5	6	5	5.3
Case Study Two				
Adequacy	4	5	4	4.3
Coherence	5	5	6	5.3
Completeness	5	5	5	5.0
Soundness	5	5	4	4.7
Usefulness	4	4	3	3.7
Case Study Three				
Adequacy	6	5	6	5.7
Coherence	5	6	5	5.3
Completeness	4	4	5	4.3
Soundness	5	4	5	4.7
Usefulness	5	5	5	5.0
Average	5.0	5.0	4.9	

Generally the results provided in table 6.9 show that the experts agree that the framework represents cutting tool design knowledge with all three cases being rated fairly highly on the rating scale. There are differences in the way the experts have rated the cases but this is due to the different viewpoints of cutting tool design knowledge they have as they all do different jobs within cutting tool design. The results in terms of adequacy have been good with two out of three experts agreeing that the knowledge represented by the cases was of an acceptable quality.

Observing the results based on coherence, it was demonstrated by the experts that they felt the knowledge represented was both logical and consistent throughout. They concede however that this would only occur if all parties were to complete the tables in an honest way and as full of information as possible. There would have to be some procedures to help individuals fill out the tables in order to show the consistency required for the knowledge representation. This suggests that the framework's usefulness in a practical situation may be affected.

The completeness of the case studies was rated as 'agree' by the experts. The case studies provided enough knowledge and information to carry out a design of similar nature. However, there are some missing items that were not available at the proposal stage. Again this shows that if the information is not provided in the first place than completing the values in the framework would be difficult. The framework provides a guide as to the level of information is required for effective cutting tool design, which would be useful to a novice or other departments of the sponsoring company.

The case studies themselves are not technically demanding therefore we are never going to get full marks in the columns and rows of table 6.9. However, they do show that cutting tool design knowledge can be structured and represented in a way that allows the knowledge to be transparent. This is especially true of the response of expert three for case two giving it a rating of 3.0 for usefulness. This is because this was for the E-Z set cutter, which in his opinion did not represent that technically a demanding example of cutting tool design and that the information provided in the case study did not provide a suitable test for the framework. However, this example was used because it demonstrated the use of calculations within cutting tool design, an example of implicit knowledge within the domain. The experts commented during informal discussions that overall the framework would be a useful tool to allow communication between themselves and other areas of the organisation. The experts agree that as a practical tool it would be very valuable. For instance, when interacting with customers it would be good to have a structure that would allow some discussion point. From a practical point of view one expert suggested that an improvement to the use of the model would be to arrange the diagrams so that each starts from the same reference point. Also he did not like the word 'ways' in each diagram. This has subsequently been removed.

6.5 SUMMARY AND KEY OBSERVATIONS

In section 6.1 the requirements for the development of an ontology-based framework for cutting tool design representation were outlined. The requirements were captured within the sponsoring organisation and called for a structured and organised approach to the representation of the 'need-to-know' vocabulary of knowledge and information. Furthermore, this representation needed to be complete and useable for a variety of applications of the intended vocabulary.

In section 6.2 the author introduces the terms function, behaviour and structure and applies them to special purpose cutting tool design. The development of an initial function-behaviour-structure model was described from the data obtained in chapter five. The terms that were identified were difficult to map to design and other domain documentation and it was noticeable that the functional terms did not take into account both the component and the cutting tool as a system. This initial model did provide a through understanding of function, behaviour and structure.

Evolution to the ontology-based framework is described in section 6.3 with the development of an ontology for special purpose cutting tool design knowledge. An ontology described on four layers was developed: component, base-functions, meta-functions, and ways of achievement and design considerations. This ways of achievement and design considerations were organised into functional hierarchies intended to solve the base-functions. In this way the domain knowledge can be represented based on these hierarchies.

In section 6.4 the ontology-based framework was tested and validated with participants from the sponsoring organisation. The testing and validation showed that the ontology-based framework was indeed complete and useful for the use in practical applications within the special purpose cutting tool design domain.

It was emphasised that the ontology was too large to use as a whole. Therefore the selection of a viewpoint from the ontology is necessary. The following chapter describes the selection of a viewpoint of design reuse. This viewpoint is then implemented onto a case-based reasoner to retrieve past designs from a case base.

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CHAPTER SEVEN

Implementing a viewpoint of design reuse

7.0 INTRODUCTION

In the previous chapter an ontology-based framework for the representation of cutting tool design knowledge was presented. It described the design considerations that were needed to achieve the functions of a cutting tool system. This model however was too detailed in its entirety for the development of applications. The reuse of past designs for the cutting tool industry is common but the selection of an appropriate past design requires experience to be done successfully. From a viewpoint of design reuse the requirements are for domain specific concepts that describe a set of designs in a database so that a user can search for and retrieve appropriate design to start the design process.

This chapter focuses on the derivation of a viewpoint of cutting tool design reuse by the identification of terms that designers use to search for designs in a database. The features of cutting tool designs were identified through the analysis of the proposal forms and designs. These features were then mapped to the ontology in chapter six to identify a set of descriptor terms that could be used to search for designs. The experts at the sponsoring organisation then individually validated the descriptor terms through semi-formal interview. The interview required the experts to rate the descriptor terms on how useful they perceived the proposed descriptor terms to be for the return of relevant past designs. The descriptor terms formed the basis for the viewpoint of design reuse in cutting tool design. This viewpoint was implemented onto case-based reasoning software and then validated for functionality and usability in the retrieval of design cases.

This chapter is structured as follows. In section 7.1 the user requirements for design reuse are outlined. In section 7.2 the development of the reuse viewpoint is presented. Section 7.3 discusses the implementation of the viewpoint onto Case Based Reasoning (CBR) software. The validation of the viewpoint in terms of functionality and usability is described in section 7.4. Section 7.5 discusses the issues pertaining to the implementation of the Case-Based Reasoning system on the sponsoring organisation. Finally the chapter is concluded with summary and key observations in section 7.6.

7.1 USER REQUIREMENTS FOR DESIGN REUSE

In this the final phase of the research the reuse of design knowledge is demonstrated by the development and implementation of a viewpoint of design reuse. To achieve this, the requirements of a design reuse viewpoint were sought from the cutting tool industry. Designers (expert and novice) and salespersons from the sponsoring organisation, designers from industry competitors such as Sandvik and Kennametal, the review of design reuse literature and the author's own observations have been included to understand and capture the requirements of these potential users. These potential users were asked during semi-formal discussions on their needs of a viewpoint for design reuse. These discussions and participation were recorded as a set of field notes and analysed at a later date for terms that described the requirements.

It is noticeable that throughout the cutting tool industry design reuse is a common practice. There is a need for the industry to be able to search for designs, recall these designs and provide a quick & ready quote for the customer. For instance, all the cutting tool industry participants reflect on the need for faster on the spot quotation facility: *"if a customer asks for something he wants designing...we need a quick way of assessing that information and then be able to design quickly and give a rough quote".* The designer continues, *"For instance, if we (the organisation) are being asked to design a tool to machine a radius arm then we should be able to search for this and provide the quote".*

However the feedback received suggests that the main concern of implementing such a system is the lack of information and a structured approach to its implementation. This lack of information means that the search results do not retrieve a close match and thus it takes several iterations to achieve a successful match. The lack of structure also poses a problem in the reuse of design information. For instance, one industry based competitor states: *"...they have many surplus inserts of which many are of similar design but of different numbers"*, and... *"if we had a database of these inserts with some information about them then it would make it easier for us to reuse them"*.

Implementing a viewpoint of design reuse would provide a structured approach to the design of cutting tools. On a further note, the research must consider the different customers of the design reuse information. A range of customers (internal to the organisation) need to be satisfied by the design reuse: both expert and novice designers, the salespersons, and then other personnel of the organisation such as the quotation department. All these users would require use of the same base of data. This requires a common understanding of the domain and its terms by all parties concerned.

There is a need for a structured approach to cutting tool design reuse. This can be achieved by developing a viewpoint of this reuse based on a formal representation of the knowledge in the domain. This viewpoint must be suitable for the task of design reuse and provide a facility for searching, recalling and reusing past designs. Secondly, it must be usable and be easy to use to reduce the time taken to retrieve designs. The next section describes the selection of the design reuse viewpoint from an ontology-based framework to represent cutting tool design knowledge developed in chapter six.

7.2 DEVELOPMENT OF REUSE VIEWPOINT FROM THE CUTTING TOOL DESIGN ONTOLOGY

This section discusses the development of a set of feature-based descriptor terms followed by the description of the development of these descriptor terms into a viewpoint for design reuse. By examining the features of cutting tool designs it has been possible to select a set of descriptor terms that designers frequently use to search for designs. These have then been mapped onto an ontology described in chapter six of this thesis. From this basis a viewpoint of design reuse has been developed. The development of the viewpoint for design reuse is presented in figure 7.1.

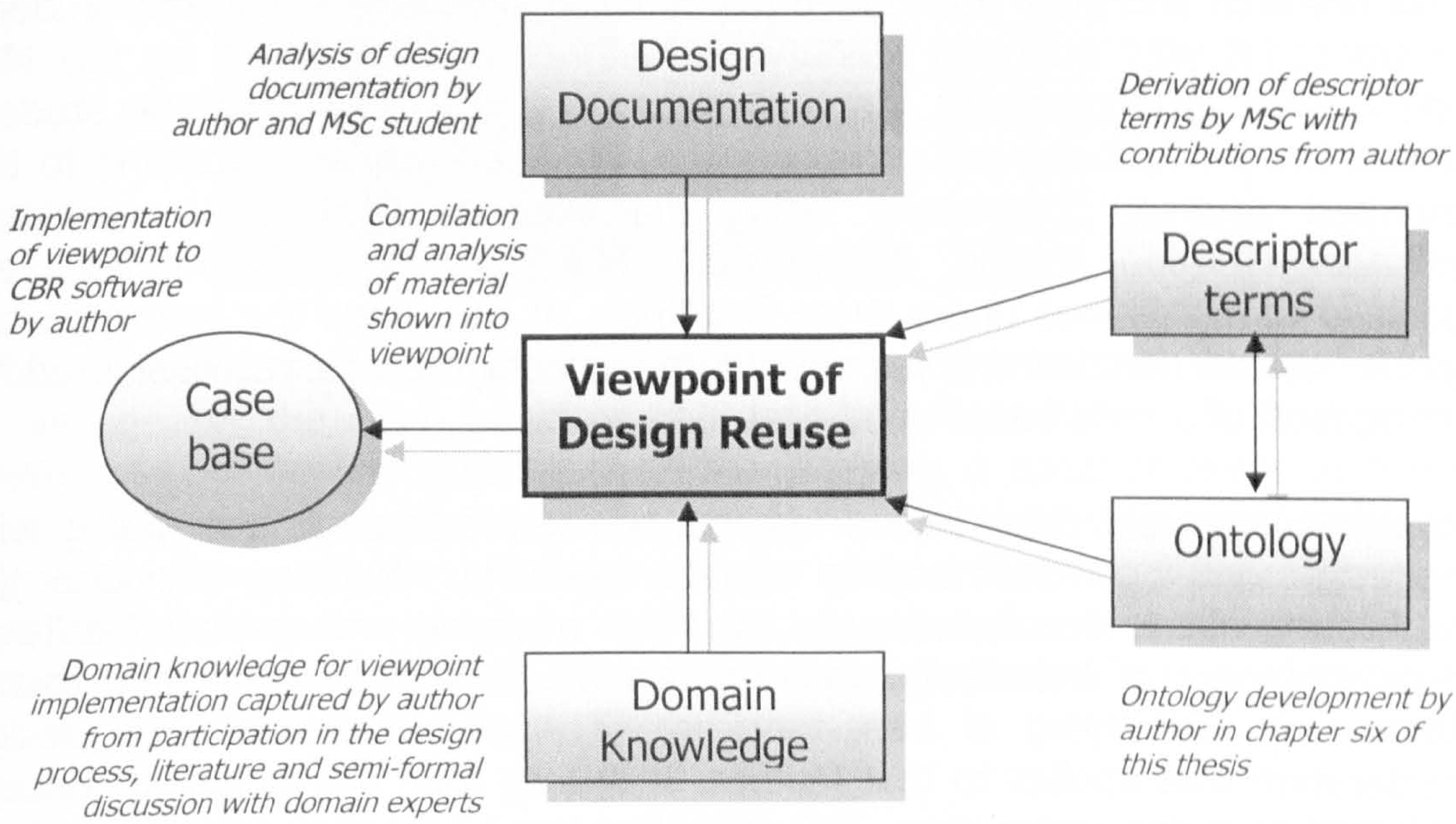


Figure 7.1: The development of the viewpoint of design reuse.

7.2.1 What is a viewpoint?

A viewpoint is the way in which a subject is observed. That is, how are we going to look at the cutting tool design domain in terms of reuse considering a variety of sources? Design by reuse relies on the availability of appropriate knowledge sources (Smith & Duffy, 2001). This reuse requires capture of knowledge from a variety of sources and viewpoints. The viewpoint chosen for this research is the viewpoint of designers at the sponsoring organisation. A viewpoint must also consider the types of domain knowledge that are incorporated into the viewpoint. The work carried out in this chapter identifies the domain knowledge to implement the viewpoint of design reuse.

7.2.2 Derivation of descriptor terms

The purpose of this section is to describe the development of a set of descriptor terms used by designers at Widia Valenite. The derivation of the descriptor terms was carried out in the work of an MSc individual project run in conjunction with this research. The author of this research was involved in the development of these descriptor terms.

The approach to the derivation of the descriptor terms was to use the KEN methodology described in chapter four of this thesis to analyse 10 sets of design documentation (proposal form and design) and identify features and attributes that were common to special purpose cutting tool design. The MSc student studied the 10 designs before undertaking the KEN methodology with an expert at Widia Valenite. This interview was recorded on video by the author of this research and later transcribed jointly by the author and the MSc student. The transcript was analysed identifying features and attributes by the MSc student with verification by the author of this research. The MSc student grouped the 64 features and attributes into initial categories pertaining to the prescribed *tooling*, *component*[1] being machined or the actual machining *application* (turning, milling, drilling etc.). The features and attributes were organised to hierarchies under these headings. At this stage the features were regarded as too detailed and too specific to the design problems considered for interrogation of a case base for other design problems.

These features were then turned into generic terms through a mapping with the design ontology described in chapter six. This mapping provided the identification of the descriptor terms. It is this mapping process that facilitates the development of the design reuse viewpoint. A feature is mapped to the ontology by identifying a base-function, way of achievement or design consideration that applies to that feature. If it does then the matching concept is selected as a descriptor term. This identified the 12 most popular 'ways' that were passed through during the mapping process. Examining these 12 most encountered 'ways' and applying selection criteria, the 16-descriptor terms were identified; these are presented in table 7.1.

The validation of descriptor terms of the descriptor terms was performed by semi-formal interview and questionnaire with 6 designers at Widia Valenite. The questionnaire was developed by the MSc student the author of this research and contained closed questions that required the designer to rate each on a scale from 1 to 6, 'strongly disagree' to 'strongly agree' respectively. Both the MSc and author were present at the interviews: the author for the ontology input and the MSc student to describe each term derived. The designers were asked to rate 16 useful searchable terms for the location of past cutting tool

[1] The term 'component' used by Hodges (2002) has been replaced by 'workpiece' to reflect the definition of the special purpose cutting tool system (see chapter 1, section 1.3.3 of this thesis).

design for reuse. Table 7.1 presents the most popular descriptor weighted to take into account of the experience of the different designers.

Table 7.1: Most popular descriptor terms (Hodges, 2002).

Searchable Term	Mean Score	Normalised Score (to most popular)
Application	0.94	1.00
Workpiece Material	0.87	0.93
Feature to be Cut	0.84	0.89
Type of Insert	0.82	0.88
Diameter of Tool	0.80	0.86
Geometry of Pocket	0.73	0.78
Depth of Cut	0.72	0.77
Chip Breaker	0.71	0.76
Through Coolant	0.71	0.76
Machine Tool	0.69	0.74
Speed of Cut	0.68	0.72
Feed Rate	0.68	0.72
Length of Tool	0.67	0.72
Type of Clamp	0.62	0.66
Size of Workpiece	0.59	0.63
Shim Dimensions	0.43	0.46

From the point of view of obtaining guidance on the important descriptor terms to include on the user interface Hodges comments that: "*It (the analysis performed on the descriptor terms) clearly shows a band of terms at the top end of the popularity scale over which there is remarkably broad agreement regarding their utility for accessing relevant designs for reuse".* He recommends that the following five descriptor terms be instantiated on the user interface for design searches: *Application, Workpiece Material, Feature to be Cut, Type of Insert and Diameter of Tool.* These were used in the viewpoint described below.

The descriptor terms in table 7.1 formed the initial viewpoint for design reuse; however this viewpoint neglects the viewpoint of a group of individuals in the organisation for which a viewpoint of design reuse would be of value. The salespersons contribute to the design process by providing the information in the proposal forms. When visiting a customer the salesperson requires access to past designs to give the customer an indication of the capability of the organisation or for a 'quick & ready quote' to a similar design found on the case base. In an attempt to gain the viewpoint of the salespersons the author invited two salespersons from Widia Valenite to express their views of the descriptor terms during a semi-formal interview. The author presented the table shown above in table 7.1 and asked the whether the terms are those they would use when visiting or preparing a proposal for design involvement. They agreed with the terms presented but also required some additions to the descriptor term list to which they would find useful. These include those shown in figure 7.2 under the category of 'commercial' and an extra descriptor term for the category 'workpiece': workpiece name. The construction of the viewpoint is described in the next section.

7.2.3 Final viewpoint for implementation to CBR software

This section describes the construction of the viewpoint from the terms found in the previous section. The final viewpoint that is used for the validation process is shown in figure 7.2. This section will describe the rationalisation of the viewpoint to this final version. It is this viewpoint that is used in the implementation discussed in section 7.3. It is organised according to the format of the ontology described in section 6.3.3, figure 6.5. The terms used in the viewpoint of design reuse are the design considerations shown in 'ways of achievement' diagrams shown in appendix C section C6.

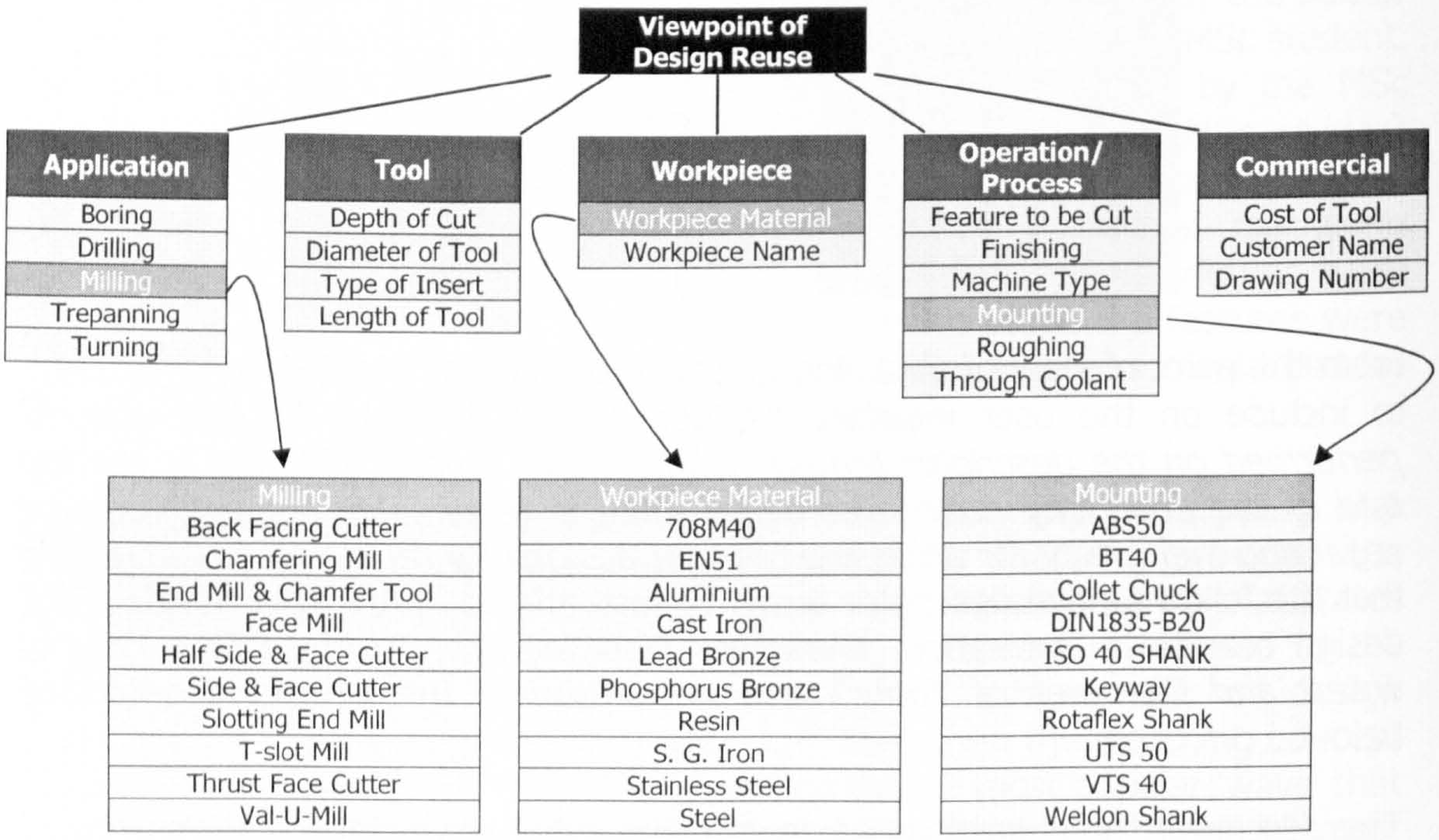


Figure 7.2: The final viewpoint of design reuse.

Organisation of the viewpoint

The categories tool, component and operation/process were categories suggested by Hodges (2002). The author of this research derives the categories 'application' and 'commercial' for the purposes described below. The attributes were organised in these categories by evaluating the attributes and placing them according to whether they were applicable to application, tool, workpiece, and operation/process and commercial. For example, the 'type of insert' is an attribute under the 'tool' category; it is obvious that the insert is a part of the tool that cuts the workpiece. In another case the attribute 'finishing' is a 'process' or 'operation' that the workpiece undergoes when the tool cuts the material.

The attribute 'application' has been transferred into a category because using 'application' as an attribute is too vague a term as it could apply to milling, turning, drilling etc. This is because there is a rich selection of milling and turning styles from which to choose at Widia. Confirmation was obtained from the designer during the interviews carried out by the MSc student and the author of this work. Rather than have these vague categories it would be beneficial that early on in the search process it be possible to search for a particular type of milling or turning tool. Hence the structure adopted for the application category. On the CBR software the user can select a milling, turning, boring, drilling 'type'.

For the salespersons the addition of workpiece name to the category 'workpiece' is required because often in the automotive industry the components (known as workpiece in this thesis) are very often similar to designs undertaken before e.g. brake calliper, cylinder head & crankshaft etc. To be able to search under the term workpiece name would speed up the process for the salespersons. The majority of the work is for big automotive and aerospace companies, starting a query based on customer name would be of benefit to get to a range of designs for that company. Having the cost information available for a past design would enable the salesperson to access a similar design to the proposed design. This enables the salesperson to provide the *"quick and ready"* quote to give an indication to the customer the approximate cost of the tooling to be supplied.

From a viewpoint of design retrieval the case-base is set up in the following way: application, tool, workpiece, operation/process and commercial as shown in figure 7.2. These are all needed to define a design in the case-base for design reuse. It is necessary because the designer receives this type of information, and the analysis in chapters four and five illustrate that these are the fields that should be modelled in the case-base. The viewpoint facilitates the description of cutting tool designs based on the knowledge and information gained in chapters four, five & six with a vocabulary or set of terms to structure the case base. The next section discusses the domain knowledge capture to populate the fields on the viewpoint implementation.

7.2.4 Domain knowledge capture

Populating the fields for the descriptor terms requires design domain knowledge. The author used a variety of sources to populate the fields shown in the screen shots within as figure 7.4 to 7.8. The domain knowledge has been captured during the activities mentioned in chapters four and five of this thesis. In chapter four, the author described the design activities that he undertook to design cutting tools for customers. Having this exposure to the types of cutting tool, types of workpiece and application types to design these cutting tools was essential. For example, when performing a design task would require the author to expose himself to a range of catalogues, past designs and interaction with design experts & salespersons. A record of the varieties of domain knowledge available was recorded as a diary of events during the period of participation. Examples of these are given in chapter four, section 4.5 as part of the industrial validation of Knowledge = Expert – Novice. The exposure to the design domain did not end after the initial 6-month participation in the design department at Widia Valenite. For the proposal form knowledge capture the author evaluated 50 proposal forms and designs for missing information during which he was able to record the types of domain knowledge that was present in the documentation studied. This is illustrated in figure 7.3.

Drawing Feature	Yes/No	Description
Cutting Envelope	Yes	Again the x-section of the component to be machined has been given with the tool placed in the position that it will begin to cut.
Depth of Cut	Yes	The depth of material cross-section shown on the drawing is **63.50**mm.
Type of Toolholder	Yes	The shaft of the drill is specified to a standard **DIN1835-B20**. This is used to attach to the machine.
Type of Insert	Yes	Standard insert **CCGT-060204 AL-1**
Pocket	No	No pocket information is given as the design here is only a proposal
Length of Cutter	Yes	Overall **length** of the cutter is given. **150mm.**
Tolerances	No	A proposal drawing would necessarily give these dimensions.
Clearances	No	A proposal drawing would necessarily give these dimensions.
Cutting Angles	No	A proposal drawing would necessarily give these dimensions.
Clamping Mechanisms	No	Insert screw used.
Chip Gash	Yes	On the drawing it is possible to see the flutes but no accurate dimensioning is given.
Orientation	No	Not given
Type of Tool	Yes	**Special boring tool** & **Special Solid Carbide drill**. The toolholder shaft is a **DIN1835-B20 mounting**.
Component	No	No real indication of the component but the design states that the material is **aluminium**.
Application/Process	Yes	A **drilling application** and a **boring application**. In which sequence the tools operate is not given. My quess would be the drill machines the initial hole then the boring bar does the chamfers etc.
Number of Inserts	Yes	**4**
Materials	Yes	**Solid Carbide** & **EN-24**
Calculations	No	Not on the drawing
Chip Breaker	Yes	Flutes on the drill
Shim Seat	No	Shims not required
Coatings	No	Coating on the insert are not given.

Figure 7.3: Knowledge exercise for a random set of proposal forms.

The author was looking for whether the features described in the figure were contained within the design documentation as an exercise in understanding the special purpose cutting tool design domain. The features were identified in chapter five and used in the initial function-behaviour-structure model (see chapter six, section 6.2.2). The 'yes/no' column two in figure 7.3 indicates whether it is possible to identify the drawing feature (column one) on the design. The description is given in the right hand column and bold items illustrate the types of domain knowledge obtained. The results of this exercise demonstrated that approximately half of the features could be mapped from the design alone. But the exercise gave the author experience of recognising design features and items of knowledge in the domain, which he was able to use in his design work and research activities. The domain knowledge types are shown in tables D1 to D4 in appendix D, section D1. Examples of the types of domain knowledge are shown in figure 7.2 for milling, workpiece material and mounting. Complete lists of the domain knowledge used to populate the CBR software are shown in appendix D section D1. The next section discusses the mapping of the viewpoint to verify that it uses the vocabulary presented in chapter six, in light of the changes made as described above.

7.2.5 Mapping of viewpoint to ontology

To ensure that the viewpoint described above still applies to the ontology (see chapter six) a mapping of the descriptor terms is illustrated in this section. This is presented in table 7.2. The mapping task involves taking all the attributes and mapping them to their location in the ontology. That is, examining the 'ways of achievement' diagrams (see appendix C section C6) and observing that the attributes are indeed present in the design considerations.

Table 7.2: Mapping viewpoint attributes to ontology.

Attributes	Way of achievement	Function
Application		
Boring	Boring Way Application Way	Produce Shape (Figure C6, appendix C, Section C6) Gain Shape (Figure C9, appendix C, Section C6)
Drilling	Drilling Way Application Way	Produce Shape (Figure C6, appendix C, Section C6) Gain Shape (Figure C9, appendix C, Section C6)
Milling	Milling Way Application Way	Produce Shape (Figure C6, appendix C, Section C6) Gain Shape (Figure C9, appendix C, Section C6)
Trepanning	Trepanning Way	Produce Shape (Figure C6, appendix C, Section C6)
Turning	Turning Way Application Way	Produce Shape (Figure C6, appendix C, Section C6) Gain Shape (Figure C9, appendix C, Section C6)
Tool		
Depth of Cut	Cost Way; Component Way Tool Way Surface Finish Way Continuous Contact Way	Increase Value (Figure C8, appendix C, Section C6) Gain Shape (Figure C9, appendix C, Section C6) Maximise Tool-life (Figure C5, appendix C, Section C6) Transmitting Force (Figure C4, appendix C, Section C6)
Diameter of Tool	Performance Way; Cutting Tool	Increase Value (Figure C8, appendix C, Section C6)
Insert Type	Tool Way Turning Way Surface Finish Way Continuous Contact Way Shim Way	Gain Shape (Figure C9, appendix C, Section C6) Produce Shape (Figure C6, appendix C, Section C6) Maximise Tool-life (Figure C5, appendix C, Section C6) Transmitting Force (Figure C4, appendix C, Section C6) Protect Pocket (Figure C2, appendix C, Section C6)
Length of Tool	Performance Way; Cutting Tool	Increase Value (Figure C8, appendix C, Section C6)
Workpiece		
Workpiece Material	Workpiece Way Performance Way; Component Surface Finish Way Cutting Force Way Power Requirement Way	Gain Shape (Figure C9, appendix C, Section C6) Increase Value (Figure C8, appendix C, Section C6) Attain Quality (Figure C7, appendix C, Section C6) Produce Shape (Figure C6, appendix C, Section C6) Maximise Tool-life (Figure C5, appendix C, Section C6)
Workpiece Name	Commercial Way	Increase Value (Figure C8, appendix C, Section C6)
Operation/Process		
Feature to be Cut	Performance: Component Way	Increase Value (Figure C8, appendix C, Section C6)
Finishing	Surface Finish Way	Attain Quality (Figure C7, appendix C, Section C6)
Machine Type	Surface Finish Way	Maximise Tool-life (Figure C5, appendix C, Section C6)
Mounting	Operation/process Way	Gain Shape (Figure C9, appendix C, Section C6)
Roughing	Required Finish Way	Remove Material (Figure 6.4, Chapter 6, Section 6.3.3)
Through Coolant	Operation/process Way	Gain Shape (Figure C9, appendix C, Section C6)
Commercial		
Cost of Tool	Tool Way	Gain Shape (Figure C9, appendix C, Section C6)
Customer Name	Commercial Way	Increase Value (Figure C8, appendix C, Section C6)
Drawing Number	Commercial Way	Increase Value (Figure C8, appendix C, Section C6)

7.3 IMPLEMENTATION OF REUSE VIEWPOINT IN CBR SOFTWARE

The purpose of this section is to describe the implementation of the reuse viewpoint shown in figure 7.2 into Case Based Reasoning (CBR) software. The users of the reuse viewpoint should be able to enter values to the corresponding descriptor terms and retrieve a design. The section describes the selection of the CBR shell, mapping of the viewpoint to the shell, development of the case base, a pilot testing phase and the evolution of the case base to the final model ready for validation.

7.3.1 Why CBR?

For data retrieval as is the case in the scenarios presented within this chapter the idea of the database could be an effective solution. Databases can store large quantities of information, maintain relationships between items, and access information rapidly (Watson, 1997). They are excellent at finding exact matches however poor they are at near or fuzzy matches. Furthermore, for interrogation of a database the information for a query has to be known. Case Based Reasoning allows the user to use natural language, find the nearest matching problem description in the case base or even a set of similar problems and/or even ask several questions to confirm the matching problem. This functionality is useful for the special purpose cutting tool design domain.

7.3.2 Selection of CBR software

During the investigations into Case Based Reasoning the author found many software that could be utilised to implement such a viewpoint: Price, ease of use (no formal programming required), a graphical user interface and those available in the public domain were the selection criteria. Most of the commercially available software was priced too high for this purpose. The commercial systems CASPIAN, CASUEL and CBR Works were available in the public domain and could be downloaded through the Internet at no charge and provided support for the author if required from the developers. There was also a number of other public domain software such as CL-Protos for example. However, use of these types of software was deemed unsuitable, as knowledge of programming was required. Many of these software products were research tools, poor availability of exercises for extending the software and text sources for understanding the source code meant that they were not easy to use.

The author therefore investigated the CBR software: CASPIAN, CASUEL & CBR Works. CASPIAN was written in C and was used by the author in demonstration of the CHEF program during meetings with research colleagues. It has a simple command line interface, which can be integrated with a graphical user interface (GUI) but again this required programming to achieve the interface. CASUEL & CBR Works were equally well suited to this application but CBR Works was obtained first of all and the author spent time developing his skill in using the software. CBR Works interface was efficient in the time it took to learn the use of the system as plenty of learning material was provided. Its interface is object orientated and visual rather than just lines of command text as was the case of some other packages available. The purpose of the exercise in this case was to illustrate the use of a viewpoint of design reuse rather than to build a complete CBR system. Thus, many of the systems investigated could also have performed the job required here but were not selected because of the criteria set out above. The next section describes the mapping of the viewpoint to the chosen CBR software.

7.3.3 The mapping of the viewpoint to the CBR software

CBR-Works 4 is a case based reasoning shell that allows users to generate their own CBR applications and with further extendibility allows interrogation through the Internet. The interface of CBR works navigates through four screens to manipulate the information of the application. The four screens are described in table 7.3. This section will describe the mapping of the viewpoint and setting up of the case base for reuse.

Table 7.3: The interface of CBR Works.

CBR-Works View	Description
Concept Manager	This view is used to enter the concepts and the properties of the concepts. The mapping of the viewpoint is performed in this area.
Type Manager	This view allows the user to define the types that are assigned to the attributes. Types include: integer, symbol, Boolean etc.
Case Explorer	This view allows the user to enter case information and also allows the user to organise the case base. Cases can be activated or deactivated because of incompleteness.
Case Navigator	This view is for the retrieval process. Also the retrieved cases are returned to this screen with the similarity rating also shown.

Concept Manager

The concept manager workspace is shown in figure 7.4. The screen shot shown illustrates a 'tree' view of the concepts within special cutting tool design. The viewpoint in figure 7.2 is mapped here. The terms commercial, workpiece, operation, application and tool become parents in the tree hierarchy as shown in figure 7.2. It is at this screen where each concept is defined within the model. The *'Special Cutting Tool Design'* has taken the place of 'Application' from the list in figure 7.2. The concepts of turning, milling, drilling etc have been denoted as child relationships in the special cutting tool design hierarchy. The case-base will store designs under turning, milling, drilling etc. The workpiece, commercial, tool and operation are considered sub-concepts in this hierarchy, which are then referenced by the turning, milling etc as required.

The descriptor terms become the attributes for the concepts defined above in figure 7.2. The attributes need to be assigned to a particular type of attribute within the case base. This is presented in table 7.4 for ease of use. The capture of domain knowledge was explained in section 7.2.4.

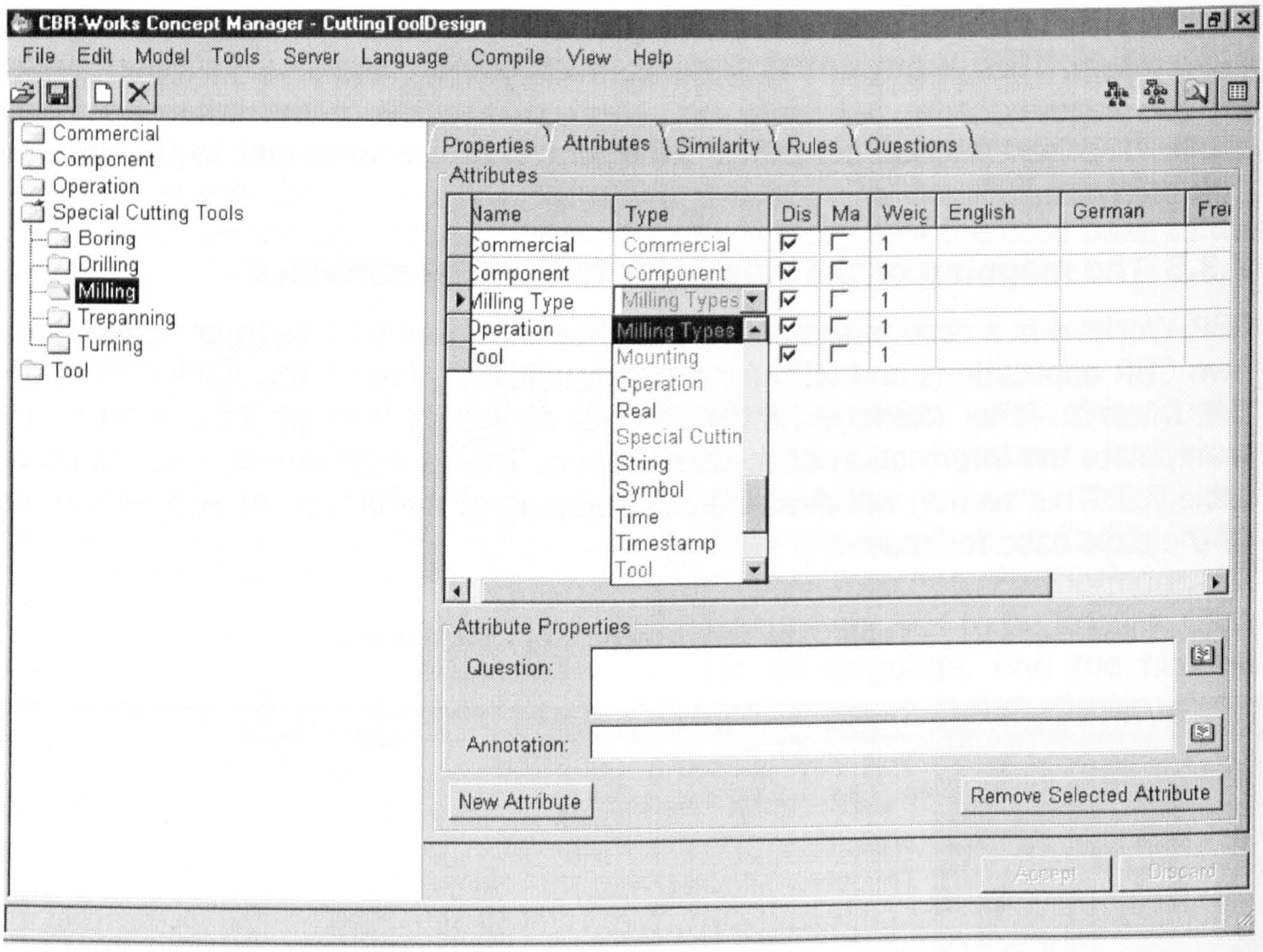


Figure 7.4: Concept Manager of CBR Works.

Taking milling as an example (this will be used through the next few sections to describe the development of a case base), we can now add attributes to the concept in this case; 'milling type' will be added under the name column. In the type column, we can now specify the type that this attribute can take. Double-click on the cell will produce a drop down menu, from here the type can be selected. The next section provides guidance to set up the types in the case base. This is illustrated in the next section, Type Manager.

Table 7.4: Assigned attribute types domain knowledge range/examples.

	Feature	Assigned Type	Domain Knowledge: Range/examples
Application	Turning	Symbol	Internal, External, Grooving
	Milling	Symbol	Face Mill, Copy Mill, Helical Cutter, Side Mill
	Boring	Symbol	Types of Boring Tool
	Drilling	Symbol	VAL-U-DEX, E-Z Set
	Trepanning	Symbol	Internal, External...
Commercial	Customer Name	String	Free text: Ford, J. A. Harris & Sons, HB Tools...
	Drawing Number	String	Free Text: S24552, U25871, T24668...
	Cost of Tool	Integer	£10 – £100,000
Tool	Insert Type	Symbol	CCMT, TPMW, SCMT, SCMW...
	Depth of Cut	Integer	0.1mm – 5mm
	Diameter of Tool	Integer	20mm – 1m
	Length of Tool	Integer	150mm – 1.5m
Workpiece	Workpiece Material	Symbol	Cast Iron, Aluminium, Steel...
	Workpiece Name	String	Free text: Brake Caliper, Cylinder Head...
Operation/ Process	Feature to be Cut	String	Free text: cylinder Bore, Side & Face...
	Machine Type	String	Free text: CNC Machine,
	Mounting	Symbol	BT50, DIN1835, ABS50...
	Through Coolant	Boolean	Yes, No
	Roughing	Boolean	Yes, No
	Finishing	Boolean	Yes, No

Type Manager

By selecting the second-from-the-left icon in the top right hand corner of figure 7.4 we can move to the *type manager* workspace. Here we can input the values for the types of attributes we have in cutting tool design. Figure 7.5 shows the type manager workspace. 'Milling Types' are placed in the 'Symbols' hierarchy. It is considered a symbol because a set of free text is to be used, as there are multiple types of milling tools. Once this folder is created, we can add the types as necessary by clicking on the 'Add' button, then typing in the value required e.g. combination cutter. The same is done for all the features identified in table 7.4. Each of the selected features that are used in the modelling of the case-base is to be defined. The selection as to whether the feature is to be assigned as a string, symbol, Integer or Boolean. This obviously depends on the type of feature that is to be modelled.

Case Explorer

The third button from the left on the top right hand corner of figure 7.5 brings the user to the Case Explorer. This is where the design cases are entered. Again a tree hierarchy is the structure of this workspace. The tree structure will show the tree created in the concept manager depicted in figure 7.4 under the name 'Special Cutting Tools'. Clicking on the '+' will expand the tree and will reveal boring, drilling, milling, trepanning and turning in this case base. Following this clicking on the '+' besides the 'milling' file will cause the expansion of the file list as illustrated in figure 7.6.

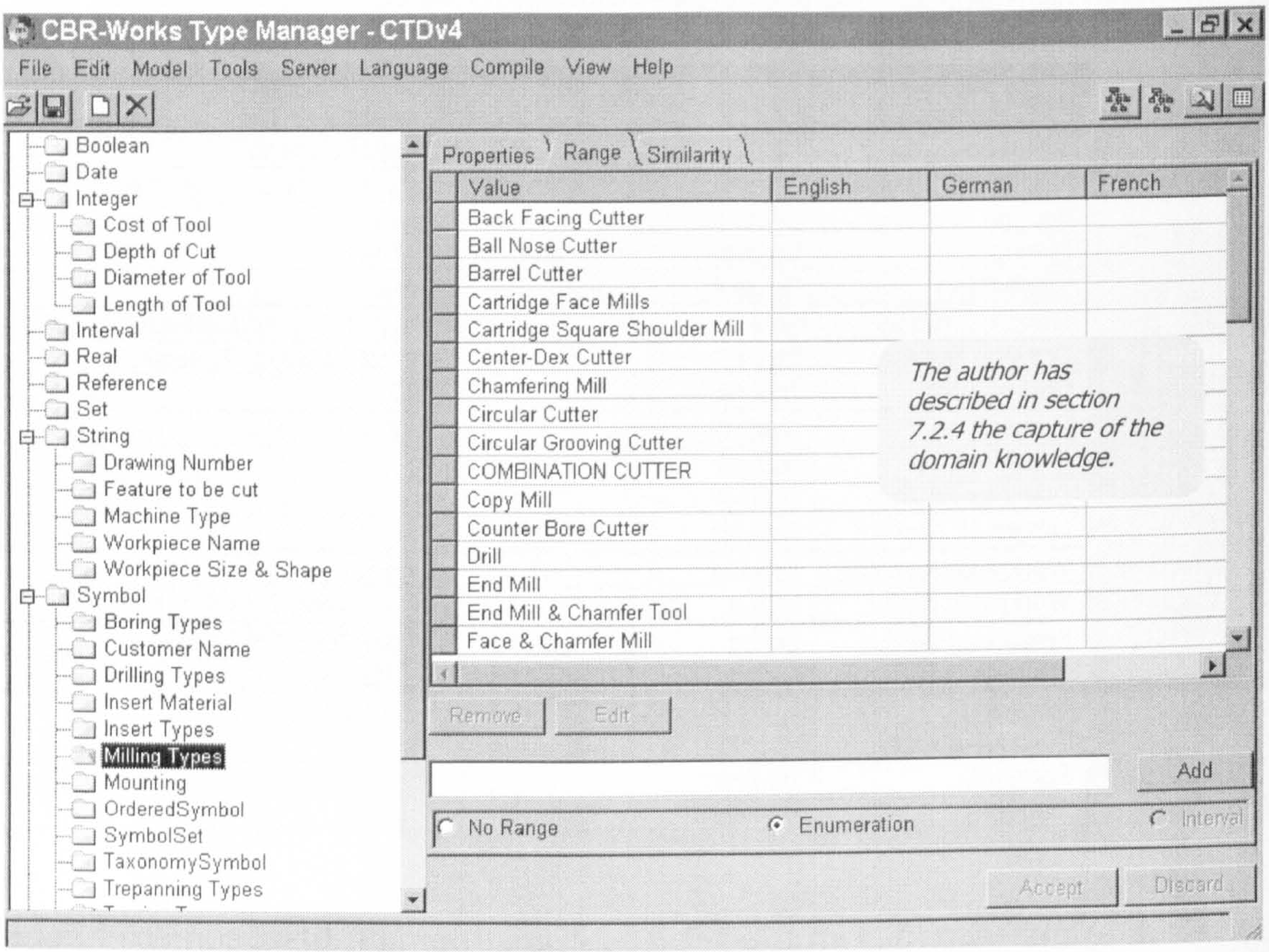


Figure 7.5: Type manager workspace.

To add a new case there are two possible ways: 1) by clicking on the third icon from the left hand side of the screen (designated by the white paper logo), or 2) by actually double clicking on the term milling itself. On each of these occasions a small screen will pop-up to allow the user to enter the name of the new case. Once this is done the pop-up screen will disappear leaving the new case with a 'red question mark' designating that it is an incomplete/unconfirmed case. Double-clicking on this icon will cause the case to be seen on the right hand side of the screen.

At this point the information for the case can be entered. The entering of case information is shown in figure 7.6 with annotations. Once the inputting of information is complete then the case can be confirmed. Once the case has been confirmed the case icon in the left hand of the screen will turn to a 'green tick'. The case base can now be used to generate queries to find past designs; this is described in the next section.

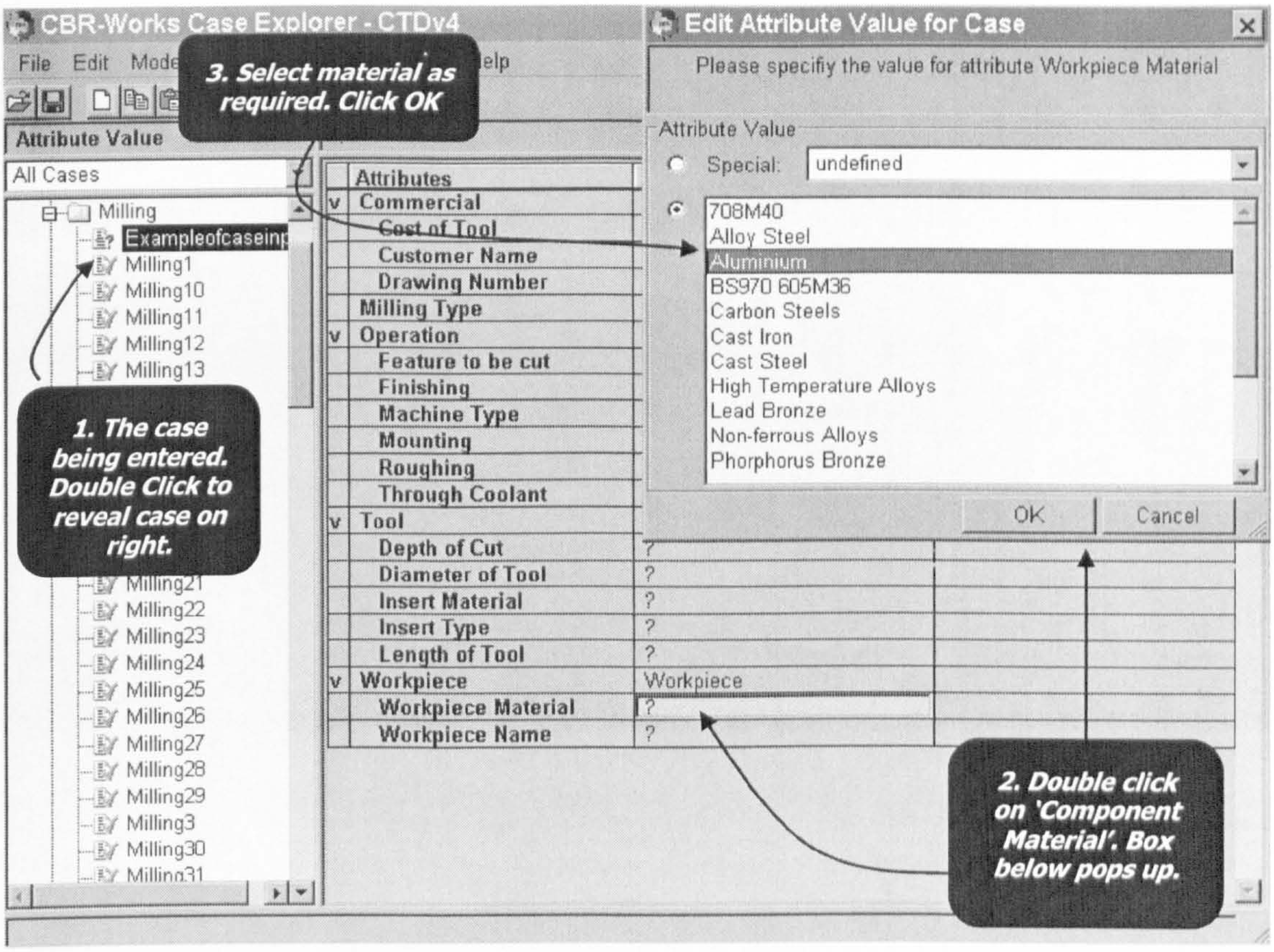
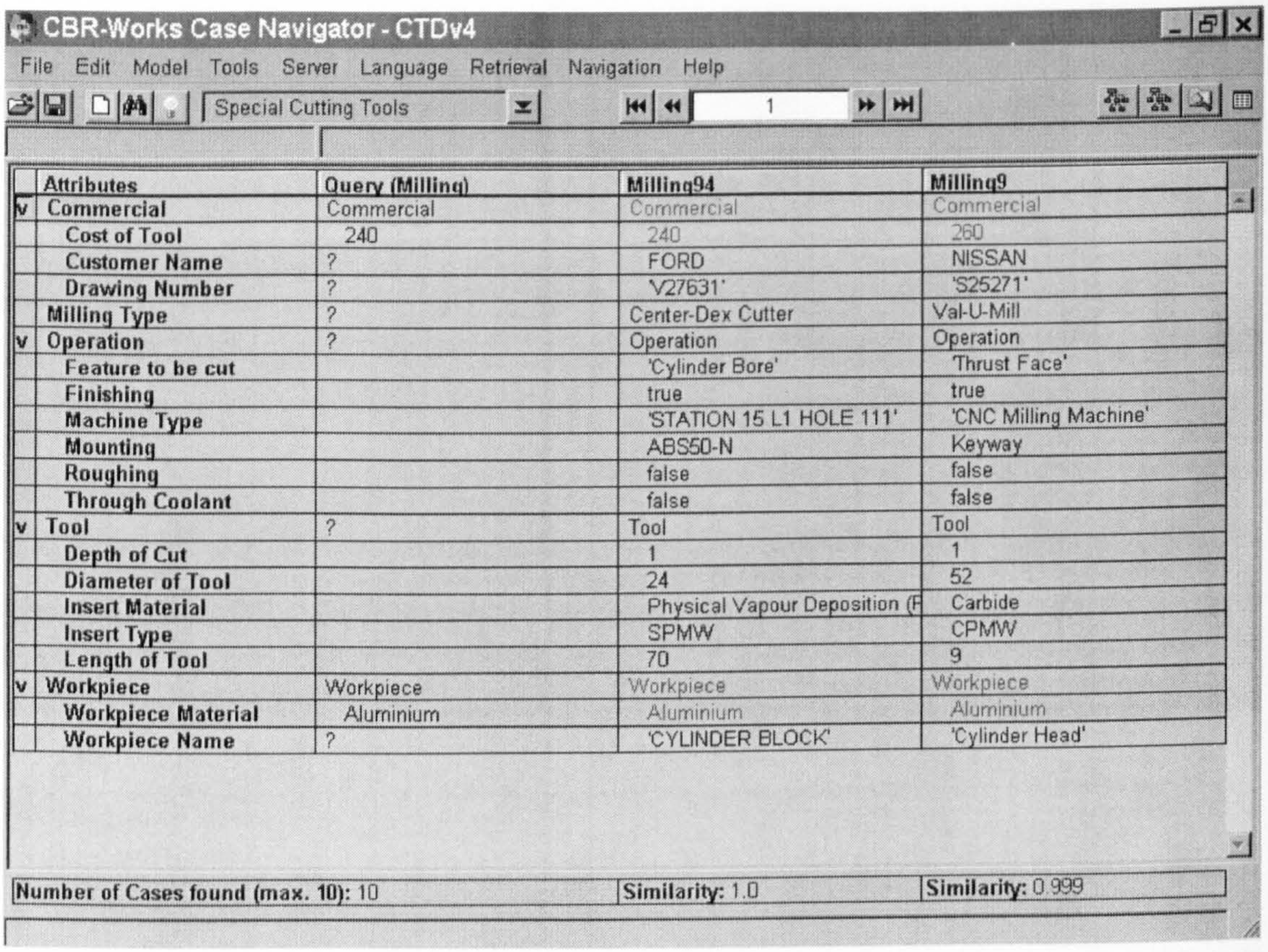


Figure 7.6: Case explorer workspace.

Case Navigator

By clicking on the far right icon in figure 7.6 one is taken to the *Case Navigator*. This is where the design retrieval takes place as shown in figure 7.7. To begin a new retrieval, select *'Retrieval'* from the toolbar. Then scroll down to new query followed by choosing the concept required in the query when prompted by the small pop-up screen. The result will be a screen similar to that shown in figure 7.7. In the second column labelled 'Query (Milling)' as we are selecting the milling concept in this case, a query term can be entered or selected depending on the type of attribute designated to that concept. For example, in figure 7.7 the value for 'Cost of Tool' was entered to the value of £240. After this entry, move back up to the toolbar and select once again select 'Retrieval', but this time scroll to 'Start Query'. The Case Based Reasoner will now search for the design/s, which matches this value as close as possible based on the internal similarity within the software. For further values enter as required depending on the level information present by the user i.e. more of the query fields could be filled in if the information was available.



CBR-Works Case Navigator - CTDv4

File Edit Model Tools Server Language Retrieval Navigation Help

Special Cutting Tools

Attributes	Query (Milling)	Milling94	Milling9
Commercial	Commercial	Commercial	Commercial
Cost of Tool	240	240	260
Customer Name	?	FORD	NISSAN
Drawing Number	?	'V27631'	'S25271'
Milling Type	?	Center-Dex Cutter	Val-U-Mill
Operation	?	Operation	Operation
Feature to be cut		'Cylinder Bore'	'Thrust Face'
Finishing		true	true
Machine Type		'STATION 15 L1 HOLE 111'	'CNC Milling Machine'
Mounting		ABS50-N	Keyway
Roughing		false	false
Through Coolant		false	false
Tool	?	Tool	Tool
Depth of Cut		1	1
Diameter of Tool		24	52
Insert Material		Physical Vapour Deposition (F	Carbide
Insert Type		SPMW	CPMW
Length of Tool		70	9
Workpiece	Workpiece	Workpiece	Workpiece
Workpiece Material	Aluminium	Aluminium	Aluminium
Workpiece Name	?	'CYLINDER BLOCK'	'Cylinder Head'

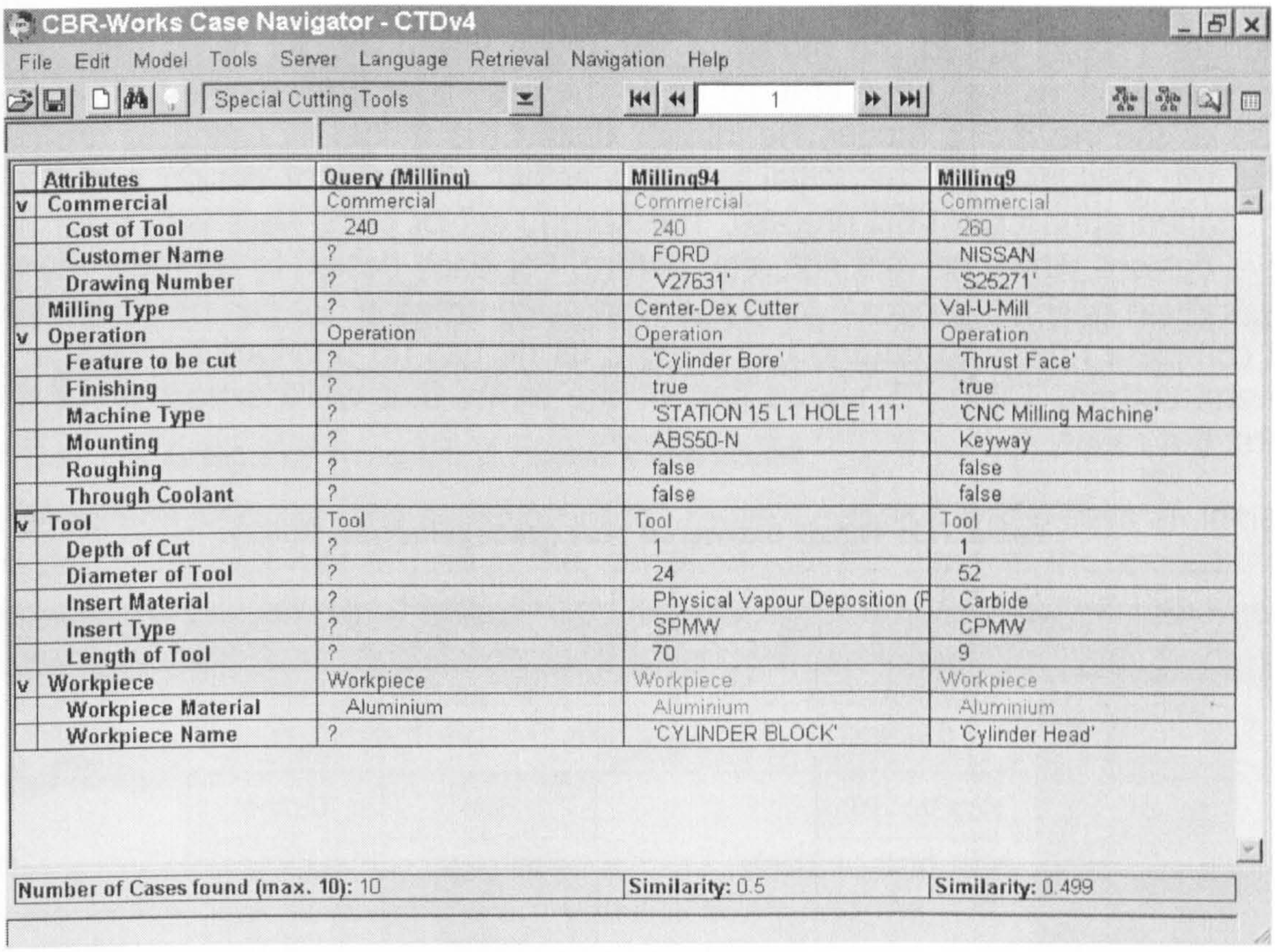
Number of Cases found (max. 10): 10 | Similarity: 1.0 | Similarity: 0.999

Figure 7.7: Case navigator workspace.

In figure 7.7 there are two retrieved cases based on the multiple attribute search performed by entering the 'component material' and the 'cost of tool', Aluminium and £240 respectively. The fields with the question marks (?) could also be used in this query if the terms are available. The next section describes how the standard software similarity metric functions.

Similarity

The default similarity values are applied to both the concepts and attributes. In this case the concepts and attributes have the same similarity rating. When a query is started the CBR engine compares the attribute-value pairs and calculates the similarity value given at the bottom of figure 7.7 for each retrieved case. Ten cases are retrieved. The similarity in this viewpoint of special purpose cutting tool design is also affected by the selection of concepts for which the attributes-value pairs are being queried. For example in figure 7.7 only concepts are selected: commercial and workpiece. Entering values for the attributes workpiece material and cost of tool at Aluminium & £240 respectively are shown. Running a search based on this selection returns similarity ratings of 1.0 for the first case and 0.999 for the second case (these are cases shown in figure 7.7). However, running the same query but this time with all concepts selected produces similarity ratings (for the same two retrieved cases) of 0.5 & 0.499. This is shown in figure 7.8.



	Attributes	Query (Milling)	Milling94	Milling9
v	Commercial	Commercial	Commercial	Commercial
	Cost of Tool	240	240	260
	Customer Name	?	FORD	NISSAN
	Drawing Number	?	'V27631'	'S25271'
	Milling Type	?	Center-Dex Cutter	Val-U-Mill
v	Operation	Operation	Operation	Operation
	Feature to be cut	?	'Cylinder Bore'	'Thrust Face'
	Finishing	?	true	true
	Machine Type	?	'STATION 15 L1 HOLE 111'	'CNC Milling Machine'
	Mounting	?	ABS50-N	Keyway
	Roughing	?	false	false
	Through Coolant	?	false	false
v	Tool	Tool	Tool	Tool
	Depth of Cut	?	1	1
	Diameter of Tool	?	24	52
	Insert Material	?	Physical Vapour Deposition (F	Carbide
	Insert Type	?	SPMW	CPMW
	Length of Tool	?	70	9
v	Workpiece	Workpiece	Workpiece	Workpiece
	Workpiece Material	Aluminium	Aluminium	Aluminium
	Workpiece Name	?	'CYLINDER BLOCK'	'Cylinder Head'

Number of Cases found (max. 10): 10	Similarity: 0.5	Similarity: 0.499

Figure 7.8: Demonstration of similarity.

The numbers of concepts that are used in the query affect the similarity in the examples above. The similarity for the first case 'milling94' returns to 1.0 once attribute values are included in the query for the other 'screened' concepts in figure 7.8: Tool & Operation. In the next section the development of the case base will be discussed.

7.3.4 Development of case-base

The values for each case in the database were mapped from the design drawings and proposal forms. It required the author to identify the features on the design drawings and the proposal forms and subsequently enter them on to the case base as described in the previous sections. There approximately 95 cases within the case base. The difficult areas to find information on are the costs and finishing details. In these situations it was required that the author questioned the experts or investigated the answers for himself from industry or academic literature and produced a realistic estimate for this exercise. It was to prove that a viewpoint of reuse could aid the retrieval of past designs. The next section discusses the pilot testing of the modelled viewpoint.

7.3.5 Pilot testing and use of the reuse model

Hodges (2002) tested the model of the reuse viewpoint. All cases that were used by Hodges had been entered on to the case base prior to the testing and use of the viewpoint model. He initially tested the model by trying to retrieve the ten designs that the initial features within cutting tool design had been identified during the KEN process. The second set of tests were with a further five designs which he had not seen before. For each design to be retrieved he was given only the proposal form and workpiece drawing. He can be considered a complete novice to cutting tool design, as he has no previous knowledge of metal cutting. Table 7.5 shows part of the terms that were extracted for the first ten cases.

Table 7.5: Terms extracted test cases (Hodges, 2002).

Descriptor Term	Problem 1	Problem 2	Problem 3	Problem 4	Problem5
Application	Drilling	Boring	Drilling	Turning	Boring
Component Material	Steel	Aluminium		Cast Iron	Phosphor Bronze
Feature to be Cut	Hole Dia. 40		Hole	Groove	
Type of Insert				TNEC	
Diameter of Tool		9.0	7		
Component Name			Camshaft	Piston	Con-rod
Customer Name	Shield Engineering	Hoburn Automotive	Ford	Kawasaki Precision	Autocraft

The extraction of terms for these first five cases was fairly easy for the novice even though several fields are incomplete. This was partly due to missing information in the proposal and design but also the inexperience of the user in filling in the missing details with tacit knowledge of the situation or even experience of cutting tool design. This was even more evident with the five cases completely new to Hodges. In these cases he found it hard to extract any terms that were useful for design retrieval from the case base. For the first ten designs he had plenty of time to examine and learn about the features in his interaction with the expert but for the second five this was not the case. He commented:

> *"...When these values were entered for the descriptor terms on the user interface, including for the terms Company Name and Component Name, in all cases the design solution returned with the highest similarity value was the original design solution that accompanied the proposal form (design specification). This indicates the effectiveness of these descriptor terms in doing their intended job of retrieval for the designs already studied. It is also an indication that, for these design problems, the descriptor terms are sufficiently relevant that a novice, with his knowledge and assumptions, can retrieve information from a proposal*

form sufficient for the retrieval of the correct design solution" (Hodges, 2002).

When the novice knew the types of feature and had the experience to fill in the missing information he was able to recall previous designs successfully. It proved that the extraction of terms from the proposal form and workpiece drawing could be used for the reuse of design knowledge. The tests revealed discrepancies in the formats of the cases entered that required attention before the validation of the viewpoint model in section 7.4. The next section describes the evolution of the viewpoint model as a result of this testing phase.

7.3.6 Evolution of modelled reuse viewpoint

This section discusses the evolution of the reuse viewpoint model from an initial model to the final model used in the validation with the users at the sponsoring organisation. The development of the final model has come from much iteration during the testing phase described in section 7.3.5. The changes that were required in the implemented model are discussed here. The figures of screenshots shown through figures and tables of sections 7.2 and 7.3 are of the final model.

The entry of text into the case base is case sensitive and also if there are any minor differences between the entry in the query and the respective cases then the similarity will be lower than expected even if all the query entries exactly match the values in the cases. The author of this research made changes to the model for the data entry. In the case of free text entry, the author made sure that all his inputs were consistent and made changes to the case base necessary e.g. 'Spigot & Annulus': in some cases this term was lower case for the 's' and the 'a' and vice versa. This standardisation was performed for each free text entry into the case base to ensure that errors could not occur in the future and where possible the free text entry were replaced by drop down menus from which terms were selected.

The work from Hodges (2002) has been extended in this work by the addition of the capture of the domain knowledge for the reuse viewpoint. Without this domain knowledge, that is the analysis of design process documentation and domain knowledge types the attributes, which were obtained by Hodges, provide no insight into the domain.

The major limitation to the work of Hodges was the testing of the design recall. All the cases used for validation were entered prior to him doing the tests. In the first five he retrieved the exact match in each case either the first or second case. In this case he was relying on the case base to give him a similarity value that was as close to 1.0 as possible, and as a novice this is quite understandable due to his inexperience in cutting tool design. This was highlighted further when he tried to retrieve cases he had not seen before. The pilot test emphasised the need for selecting design cases that were not included in the case base.

This is because a novice would not have complete grasp of the domain knowledge. Having the descriptor terms without the domain knowledge (the types of tool but not how to analyse the designs and knowing where to find information on the documentation) to use them has hindered his design retrieval. In order to overcome these problems one can help the novice by providing a guide to highlight where the information and knowledge can be found in the domain. To provide a novice with these kinds of facilities would be of great benefit. These issues are discussed at greater length in chapter eight of this thesis.

This section has described the mapping of the viewpoint of design reuse on the CBR software and has discussed the use of the CBR software workspaces to develop the model within the case based reasoner. With modifications made to the cases in the case base it was possible to begin the validation process with the experts at the sponsoring organisation, which is described in the next section.

7.4 VALIDATION OF THE REUSE VIEWPOINT

The previous sections have described the selection and implementation of a design reuse viewpoint. This section describes the validation of the viewpoint of design reuse taken from the ontology-based framework in chapter six for cutting tool design. The purpose of the validation is to test that the viewpoint of cutting tool design reuse enables designers to select the appropriate queries from the proposal form documentation to access the right design. In the next section the approach taken to test the viewpoint is described. Section 7.4.2 illustrates a typical case study used within the validation process to retrieve designs, followed by the process of the validation in section 7.4.3. The analysed results are then presented in section 7.4.4.

7.4.1 The approach

The approach was to test the implementation of the viewpoint by design cases. Each design case is the product of proposal documentation (proposal form and workpiece drawing). The designs have been created from this documentation and as such information and knowledge in the proposal documentation should lead to the right design providing the terms used to search for the design are appropriate. The participants of the validation process were required to examine the five cases and extract the terms that were appropriate to the viewpoint attributes. Then using these terms interrogate the case base to identify the appropriate or similar design. The tests performed were measured for success by the following criteria: the *effectiveness of data extraction*, the *effectiveness of the search* for the appropriate design and the *effectiveness of* *the recall/reuse* of the designs. A fourth measurement was to test the *usability* of the CBR software.

The next section describes how these requirements were tested using a questionnaire and a set of five cases. A sample questionnaire can be found in appendix D. Five designers (four experts and one novice) and 2 expert salespersons validated the viewpoint over a period of two days. The interviews results in informal discussions, which were recorded and later transcribed to support the material gathered from the written feedback given on the questionnaires.

Experiment design

Five designs were selected at random. Designs one & two were in the case base. Designs three to five were not included in the case base. During the validation the actual designs were hidden from the participant and revealed once they had completed the exercise for each case. The purpose of the design case split two to three was to demonstrate the a similar design could be retrieved that could be used even though not exactly matching the original.

Proposal documentation (proposal form and workpiece drawing) was collated for these five designs. For the experiment to validate the viewpoint in terms of reuse: the purpose was to show that the terms (required for searching the case-base, recalling a past design and then reusing this information) could be extracted from the proposal documentation. The terms entered by each participant, the attributes the participants found most difficult to obtain from the proposal information and the similarity ratings found by inputting the terms extracted were recorded. The participants were also asked to describe their reasons for difficulty in the extraction of the terms and input to the implemented system. The next section describes the design of the questionnaire.

Questionnaire design

The questionnaire was designed to gain the most out of the validation process for the requirements developed above. The questionnaire was split into four sections. The first three sections demonstrate the effectiveness for extracting design terms, the effectiveness for searching for designs and the effectiveness of the recall/reuse of design cases. The final section was to test the usability of the CBR software on which the viewpoint of design reuse was based. An example questionnaire can be found in appendix D3 including the responses of user one.

The questionnaire was designed with closed questions, which required the participant to reply to the questions bound by scale from 1 to 6. This is shown in figure 7.9 with question 6 from section 2a of the questionnaire.

These attributes would improve our design searches (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	6
Explain the reason for your choice:					

Figure 7.9: An example of the format for closed questions.

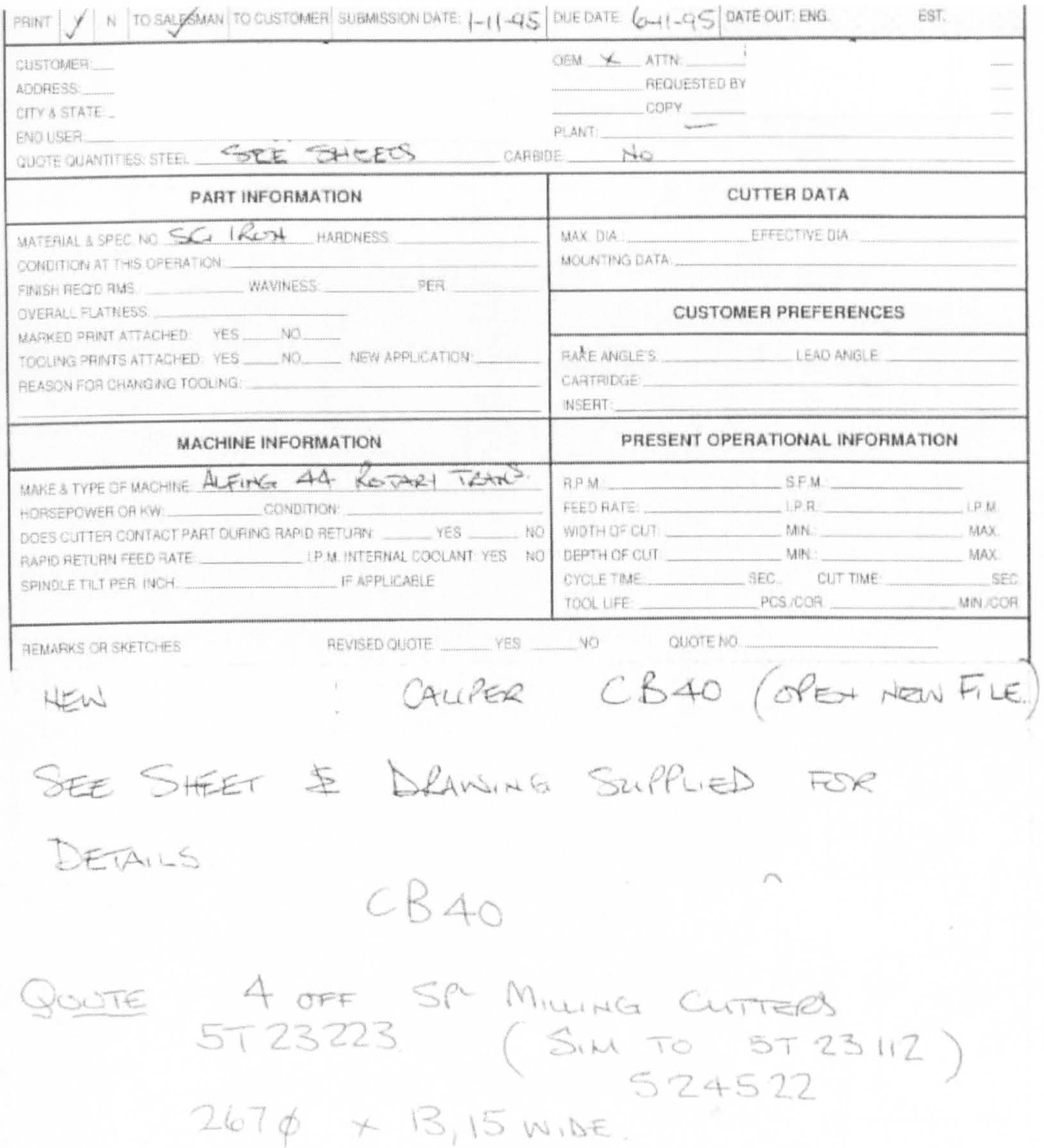
The benefit of using such questions is the ease of analysis that they offer by allowing a structured approach. However a gain in one area leads to a common problem with such questions in that the participants may be restricted in their responses. In an effort to achieve a compromise to this problem the participants are invited to comment on their choices given their response to the questions. The cases used in the experiment are discussed in the next section.

7.4.2 Case studies for design reuse

The previous section presented the purpose and the method of how the validation was to be carried out; within this section the cases are discussed. The design of a special cutting tool requires a consideration of the design issues that arise from the proposal documentation. The designer selects a past design, which reflects the closest match to form the solution to the new proposal. However, the selection of this past design requires a vast amount of experience to select the appropriate design to use. This problem is even greater for novices of the domain. The purpose of the viewpoint implemented onto the Case-Based Reasoner is to provide a functional and usable guide to the selection of past designs. Thus reducing the long search times required for retrieving the correct design. Case one is presented here, whilst the cases two to five are presented in Appendix D2. Extracting terms from the proposal documentation to use as search values for the attribute fields on the case base is required by each of the participants. This is similar to how an expert designer would consider searching for past designs on a more traditional basis i.e. without the use of an implemented system.

Case one

In this case both the proposal form and workpiece drawing are given to the designer shown in figure 7.10 and 7.11 respectively. The total design package for this proposal is to develop a set of cutting tools but for this case in the validation only the "4 off milling cutters" are to be retrieved using the viewpoint implemented in the case-base. The design to be retrieved in this case is a milling tool that is required to cut the internal side and face of the brake caliper at a radius of 133.7mm.



PRINT ✓ N | TO SALESMAN ✓ | TO CUSTOMER | SUBMISSION DATE: 1-11-95 | DUE DATE: 6-11-95 | DATE OUT: ENG. | EST.

CUSTOMER:
ADDRESS:
CITY & STATE:
END USER:
QUOTE QUANTITIES: STEEL SEE SHEETS CARBIDE NO

OEM ✗ ATTN:
REQUESTED BY
COPY
PLANT:

PART INFORMATION

MATERIAL & SPEC NO. SG IRON HARDNESS
CONDITION AT THIS OPERATION:
FINISH REQ'D RMS. WAVINESS PER
OVERALL FLATNESS:
MARKED PRINT ATTACHED: YES NO
TOOLING PRINTS ATTACHED: YES NO NEW APPLICATION:
REASON FOR CHANGING TOOLING:

CUTTER DATA

MAX. DIA.: EFFECTIVE DIA.
MOUNTING DATA:

CUSTOMER PREFERENCES

RAKE ANGLE'S: LEAD ANGLE
CARTRIDGE:
INSERT:

MACHINE INFORMATION

MAKE & TYPE OF MACHINE: ALFING 44 ROTARY TRANS.
HORSEPOWER OR KW: CONDITION:
DOES CUTTER CONTACT PART DURING RAPID RETURN: YES NO
RAPID RETURN FEED RATE: I.P.M. INTERNAL COOLANT: YES NO
SPINDLE TILT PER. INCH: IF APPLICABLE

PRESENT OPERATIONAL INFORMATION

R.P.M.: S.F.M.
FEED RATE: I.P.R. I.P.M.
WIDTH OF CUT: MIN.: MAX.
DEPTH OF CUT: MIN.: MAX.
CYCLE TIME: SEC. CUT TIME: SEC.
TOOL LIFE: PCS./COR. MIN./COR.

REMARKS OR SKETCHES REVISED QUOTE YES NO QUOTE NO.

NEW CALIPER CB40 (OPEN NEW FILE)
SEE SHEET & DRAWING SUPPLIED FOR DETAILS
CB40
QUOTE 4 OFF SP MILLING CUTTERS
5T23223 (SIM TO 5T 23112)
524522
267φ × 13,15 WIDE

Figure 7.10: Proposal form for case one.

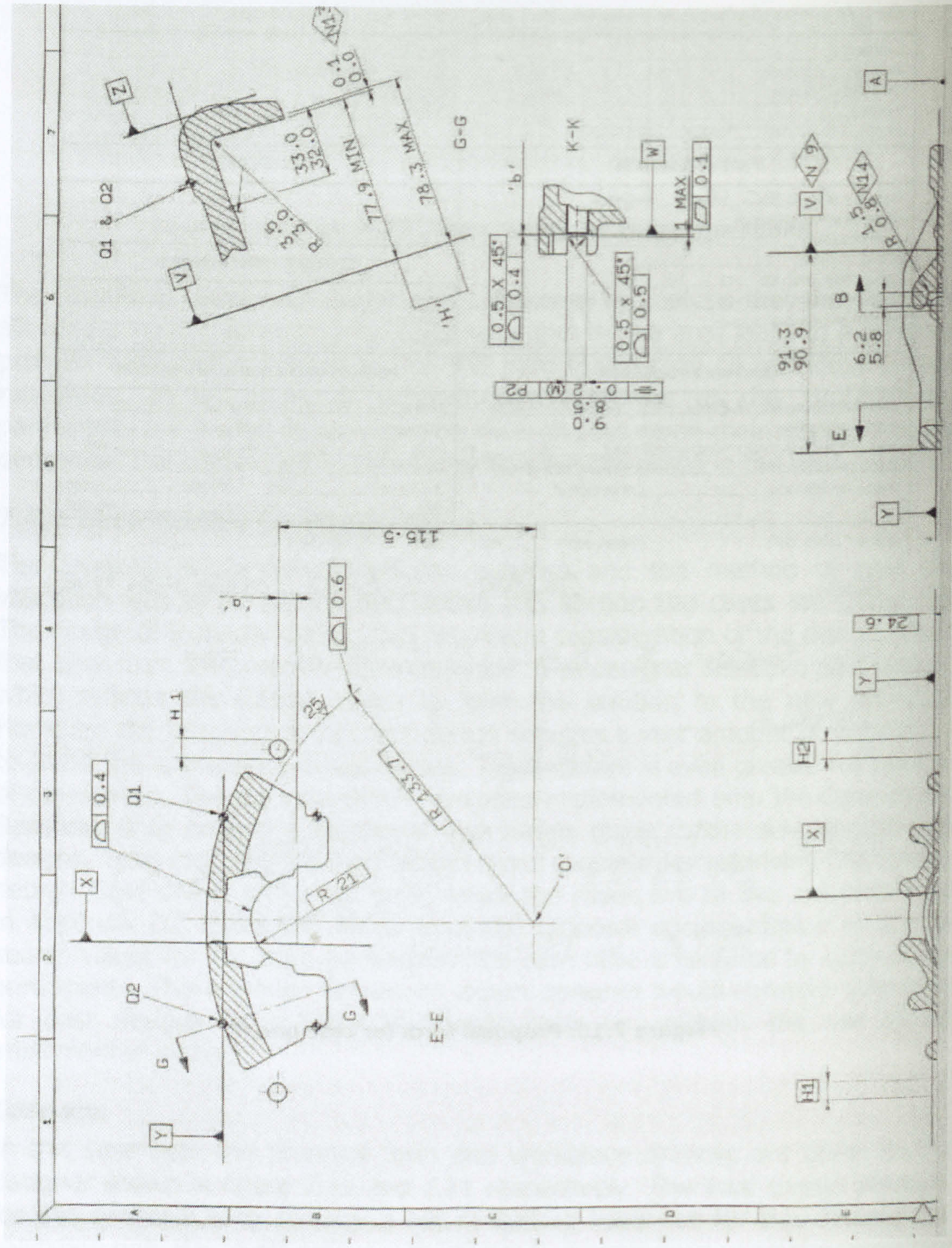


Figure 7.11: Cross-section of brake caliper for case one (part-of).

The information for this case retrieved for this case corresponds to the design shown in figure 7.12. This design is then manufactured to machine the face and sides at the radius of 133.7mm. In the validation process the participants did not see this design until they had carried out the design retrieval.

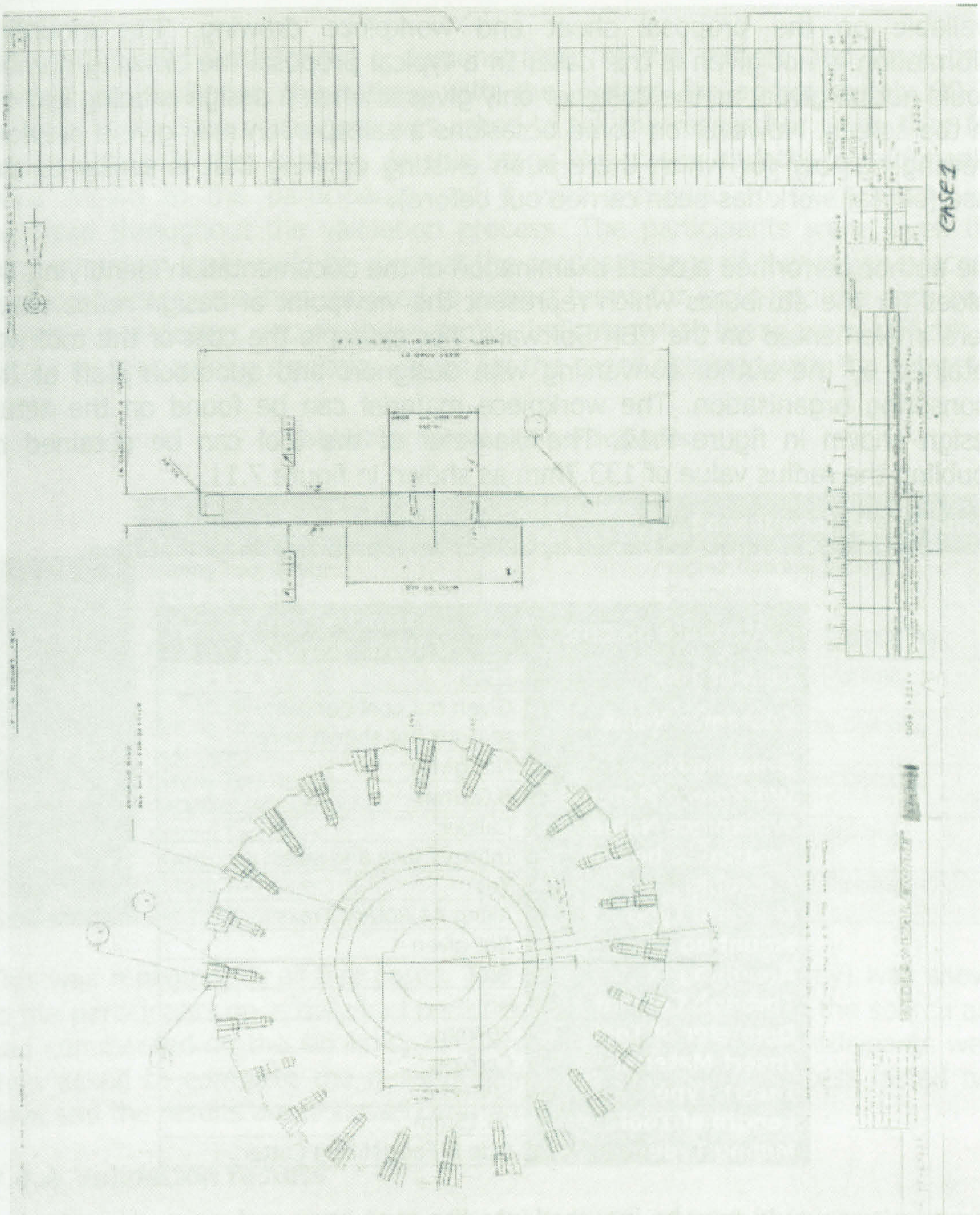


Figure 7.12: Corresponding design for case one.

The information that can be extracted from this proposal is shown in table 7.5. This is data extraction is by the author shown here as a demonstration of the typical terms extracted of the design documentation. The terms are shown with the corresponding attribute ready for searching on the case-base. There is one field (customer name), which for confidentiality is not shown here but is available on the proposal sheet and workpiece drawing. The mounting information is not given is this case. In a typical proposal the drawing number would not be given, as the designer only gives it when a design is being laid out on the screen. However on some occasions a salesperson may give a previous drawing number for which there is an existing drawing that is similar to this case (similar work has been carried out before).

The author performed a detail examination of the documentation identifying the values for the attributes which represent the viewpoint of design reuse which were implemented on the CBR Software. For example the cost of the tool was obtained by the author conversing with designers and quotation staff at the sponsoring organisation. The workpiece material can be found on the actual design shown in figure 7.12. The diameter of the tool can be obtained by doubling the radius value of 133.7mm as shown in figure 7.11.

Table 7.5: Terms extracted by author from proposal documentation.

Attribute on CBR	Extracted term (Attribute value)
Cost of Tool	£300
Customer Name	Given but confidentiality reasons not shown here
Drawing No.	Not given
Workpiece Material	S.G. Iron
Workpiece Name	Caliper
Feature to be Cut	Internal face and sides
Finishing	Yes
Machine Type	Alfing 44 Rotary Traxs
Mounting	Not given
Roughing	No
Through Coolant	No
Diameter of Tool	267mm
Insert Material	Carbide
Insert Type	SPE-422
Length of Tool	13.15mm
Milling Type	Side & Face Milling Cutter

These values would now be inputted into the case-base and a search performed as described in section 7.3.3. The section has described case one of five used in this validation (the others can be found in appendix D2). The following section discusses the validation process.

7.4.3 Validation Process

The purpose of the validation is to test that the viewpoint of cutting tool design reuse enables designers to select the appropriate queries from the proposal form documentation to access the right design. To meet these requirements four expert designers, one novice designer and two salespersons tested the viewpoint. A summary of the profiles of each participant is given in table 7.6.

The participants were given a demonstration of the system and were then allowed to familiarise themselves with the system for approximately 20-25 minutes each. Each participant was asked to tell the researcher when they felt comfortable with the system. At this stage the cases and the questionnaire were shown to the participants and it was explained to them what was expected throughout the validation process. The participants were given the documentation that would be given at the proposal stage of the design process. Each participant was then required to extract terms for input into the case-base to retrieve a design, record these terms, indicate what terms were difficult to obtain and record the similarity values for the cases obtained with the extracted terms.

Table 7.6: Profiles of participants.

	Job Role	Experience (Years)	Educational Background
User One	Cutting Tool Design Chief Engineer	>20	Higher National Diploma, Engineering
User Two	Cutting Tool Design Oil Industry Product Specialist	>20	Graduate Level, Engineering
User Three	Cutting Tool Design Tool Design Apprentice	1 to 5	Higher National Diploma, Manufacturing
User Four	Cutting Tool Design Tool Designer	>20	Ordinary National Diploma, Manufacturing
User Five	Cutting Tool Design CAD/Tool Draughtsman	>20	Ordinary National Diploma, Engineering
User Six	Cutting Tool Sales Distribution Manager	>20	Higher National Diploma, Manufacturing
User Seven	Cutting Tool Sales Sales Manager	>20	Higher National Diploma, Engineering

This was repeated for all five cases. The actual design (hard copy) was shown to the participants once they had performed the data extraction, the search and had commented on the similarity of the cases retrieved. The participants were then asked to complete the questionnaire. The validation process lasted two days and the results are discussed in the next section.

7.4.4 Validation results

This section presents and discusses the results obtained from the above-mentioned validation of the implemented viewpoint of design reuse. This is achieved with feedback from the seven participants. By using the cases given to them by the author they were able to assess the functionality and usability of the implemented viewpoint of design reuse. Tables 7.7 to 7.12 illustrate the analyses of the results from the questionnaire. These are then augmented with issues raised through informal discussion with the participants during the validation process.

Effectiveness for the extraction of terms

The results for the extraction of terms from the proposal are summarised in tables 7.7 and 7.8. Table 7.7 presents the summary of the terms extracted by user one and user three, an expert designer and the novice designer respectively. Table 7.8 illustrates the difficulty users one and three had in extracting terms from the documentation. Cases 1 & 2 are darker to indicate that they are present in the case base. Table 7.8 presents a summary of the five best cases returned by user one and three. For this user test all four concepts on the CBR interface were being used.

The participants were asked to extract terms for the attributes, which they had seen on the screen during their familiarisation time. In the extraction of values obtained for use in the searches it was interesting to note that the expert cutting tool participants (those with greater then 20 years experience) did not extract all the values that were available to them but rather relied on those that they were familiar with and had used before as a method of comparison. The expert designer stopped searching at a point where he felt comfortable that he had found the design closest to the providing a solution to the posed problem. He began his searches with the most important features (according to his experience in searching for appropriate designs) first then gradually going into less important features for a more detailed search.

Table 7.7: Terms extracted by users one & three.

	User One (Expert)				
Attribute	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Customer Name	Lucas	Nissan		Cutting Tool Supplies	Ford
Feature to be Cut					Bore & Chamfer
Mounting					Adaptor
Diameter of Tool	267	50	75	18	12
Insert Type				SD-322P	
Length of Tool	13		14		45
Milling Type	Grooving	Half side & face cutter	Grooving	Form cutter	
	User Three (Novice)				
Attribute	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Customer Name	Lucas	Nissan	Albon	Cutting Tool Supplies	Ford
Drawing No.					D27636
Workpiece Material	S. G. Iron	Aluminium	Cast Iron	Stainless Steel	
Workpiece Name	Brake Caliper	Cylinder Head	Flywheel	Artificial Joint	
Machine Type	Alfing 44 Rotary				
Diameter of Tool	267			18	
Insert Type				SPMW	
Length of Tool	13				
Milling Type	Milling cutter	Thrust face cutter	Slotting cutter	Milling cutter	

Table 7.7 reveals interesting search strategies between the expert and novice (lower half of table 7.7) in this study. Obviously the expert uses fewer terms in

general to use during a search. The values given in table 7.7 are the total number of terms used by the expert; however during his searches he used an interesting strategy. Using case 3 to illustrate, the first terms he extracted were the diameter of the tool and the milling type that he thought would do the job. With these two terms he interrogated the case base and found a number of designs – he discussed with the author that he had an idea of which would be the closest design without looking at the similarity values. This was case 3 as indicated in table 7.8 with a value of 0.5 (bold with a dark square). The expert then inputted the third term 'length of tool' and he was sure that this could be a suitable design. He used this type of strategy for the other four designs also. It is worth noting that the similarity ratings for the first two cases are low at 0.665 & 0.5 but the right designs are retrieved first. Again the expert was satisfied that these were the drawings.

Table 7.8: Similarity values for five retrieved cases for user one & three.

Note: the bold and darker cells indicate the right case or similar design.

Similarity values for retrieved designs

	User One (Expert)				
Query (Entered)	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**
Case 1	**0.665**	0.659	0.647	0.625	0.333
Case 2	**0.5**	0.497	0.497	0.497	0.477
Case 3	0.98	**0.5**	0.495	0.494	0.493
Case 4	**0.499**	0.496	0.486	0.333	0.319
Case 5	0.332	0.327	**0.323**	0.323	0.318

	User Three (Novice)				
Query (Entered)	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**
Case 1	**0.652**	0.578	0.49	0.481	0.395
Case 2	**0.392**	0.378	0.3	0.3	0.3
Case 3	0.496	0.265	**0.262**	0.25	0.25
Case 4	0.303	**0.301**	0.298	0.297	0.296
Case 5	0.208	0.187	0.166	0.166	0.166

The novice designer in this case extracted double the amount of terms to use for the searches. This is reflected in the similarity values obtained. For the novice the similarities are higher than those of the experts. This is due to the method by which the case-base reasoner applies its similarity metric; it is based on attribute-pair matching. Thus when the expert designer does not input all the values possible it matches with a far smaller number of attributes than that of the novice. However, the participants did not rely on the similarity value obtained for the retrieved cases for their justifications as to why the case they had selected was correct.

In terms of matching the exact design or finding a similar design within both the first two cases, the users both retrieved the right design either as the first case or as the second case. For cases 3 to 5 it was a different story. These three cases were not on the case base as were the first two. Therefore the users were looking for similar designs to be retrieved. In the expert's retrieval he found three cases that were similar or he realised that he could use parts of them. The novice on the other only retrieved a similar design for case 3 on the basis that work had been carried out for a flywheel previously but of different material. Case 5 did not return useful designs other than designs with the word 'FORD' throughout and some matching of numerical values with the drawing number entered: D27636. The case base reasoner matches V**276**31 for the first three numerals and T**27**334 for the first two numerals. However he was unable to select a suitable case. For case 4 he was more successful because he was able to input more extracted terms and a selection of a case was made.

The expert was able to match more of the similar designs, which provides an interesting observation. The values for case 5 the author believes were performed from memory or experience, as these values extracted by the expert were not on any documentation provided by the author. Yet he was able to extract these terms and hence was more successful in his retrieval.

The time taken to input the terms extracted from the proposal documentation reduced from an initial 15 minutes to 3 minutes average once the user gained experience in using the system. The majority of the time used here was for extracting the terms from the proposal information. The response from all participants was that this time is acceptable as very often searching for designs by memory and case-by-case took far longer. This is encouraging as one of the requirements stated by industry has been a reduction in the length of time that it takes to search for similar designs.

Effectiveness of searching for design cases

After the participants had searched for the designs based on the given cases, they were required to answer the questions found in table 7.9. It can be seen that the overall effectiveness for searching cases was positive. With the lowest average rating across questions at 4.9 (6 is the maximum) for question five and the highest being 5.7 for question six. In terms of the individual participant ratings users 4, 5 and 7 give the lowest ratings at five each. On the rating scale devised this relates to a scoring of 'agree'.

Table 7.9: Effectiveness for searching for design cases (average ratings).

Q	*Effectiveness of searching for design cases*	Rating 1 - 6							
		User1	User2	User3	User4	User5	User6	User7	
4	The cases are representative of the cutting tool design domain.	5	6	5	4	6	5	5	5.0
5	The attributes are appropriate for the viewpoint of cutting tool design reuse.	4	6	5	4	5	5	5	4.9
6	The use of these attributes would improve our design searches.	6	6	6	6	5	6	5	5.7
7	The viewpoint would help us to store our designs in a consistent manner.	6	6	6	6	4	5	5	5.3
		5.3	6.0	5.5	5.0	5.0	5.3	5.0	

The 4.9 average given by the participants seems slightly disappointing, however on further investigation into the comments made by users 1 and 4 (the lowest ratings of the participants) can reflect the low score obtained. It was their opinion that some of the attribute values that were inputted into the system needed expanding further to incorporate the different varieties of names that a tool can take within the industry. The attributes themselves were not lacking as demonstrated by the analysis performed in work of Hodges (2002). Thus the viewpoint implemented requires further examples of tool to be inputted into the case base i.e. more than one hundred cases are required. This is because a viewpoint of design reuse should include the types of domain knowledge as well as the attributes used to search for them. If no domain knowledge was incorporated then the viewpoint would not be useful. The second section of the questionnaire required the participants to assess the effectiveness of the recall of a past design i.e. how close the match in their opinion for practical design tasks was.

Effectiveness of the recall designs

It is noticeable from the average values obtained in table 7.10 that overall effectiveness of the recall of cases is positive. However two areas are highlighted as areas for discussion. These are the areas of question 2: "the viewpoint provides a common understanding of cutting tool design" and question 5: "the viewpoint would help us to make better quotations".

Table 7.10: Effectiveness of the recall of a past design case (average ratings).

		Rating 1 - 6							
Q	*Effectiveness of the recall of designs*	User1	User2	User3	User4	User5	User6	User7	
1	The appropriate design solution was returned in each case.	5	6	5	6	6	5	5	5.4
2	The viewpoint provides a common understanding of cutting tool design.	4	5	5	5	5	5	4	4.7
3	The design reuse viewpoint is useful for sharing information between sales and design.	5	6	6	5	5	5	6	5.4
4	The viewpoint would help us to make informed decisions at the proposal stage.	6	6	5	6	6	6	6	5.8
5	The viewpoint would help us to make better quotations.	6	5	4	4	5	5	5	4.9
		5.2	5.6	5.0	5.2	5.4	5.2	5.2	

It is interesting to note that an expert designer (user 1) and an expert salesperson (user 7) have highlighted this in their individual ratings also at '4' each considering their different needs of a viewpoint for design reuse. Their concern was that the potential for a common terminology was evident from the viewpoint and hence slightly agreed with question 2. However as the case-base grew it would become more difficult to confine people to describe the tools unless a common terminology for the inputting of data was addressed. Different users of the viewpoint would put their own values to the attributes. Thus a common terminology will lead to a common understanding.

The low assessment for the question 5 (as to whether the viewpoint can be effective in order to produce better quotations) was to the difficulty in recording cost information. Within this viewpoint it is not usual to have this quotation information, as it is not performed by either designers or salesperson but by specialist quotation engineers. The argument being that this knowledge and information would have to be incorporated in order for it to become a valuable resource in this respect. They concede however that if it were available then this would very effective for reuse of cutting tool design knowledge. The next section of the questionnaire addresses the need for reuse of cutting tool design cases.

Effectiveness for reusing designs

Table 7.11 summarises the average ratings for the reuse of design cases when using the viewpoint. It is shown that the reuse of design cases is very positive.

Table 7.11: Reusing design cases (average ratings).

		Rating 1 - 6							
Q	*Effectiveness of reusing designs*	User1	User2	User3	User4	User5	User6	User7	
1	If people involved with these designs had left the company, this information would be invaluable.	6	6	5	5	5	6	5	5.4
2	This information would help me to start the next design.	6	6	4	5	6	5	5	5.3
3	This information is invaluable for a novice to the cutting tool industry.	6	6	5	5	6	5	6	5.6
4	This information would be useful for future in cutting tool design.	5	6	5	5	6	4	4	5.0
5	With the viewpoint, the design lead-time will be reduced in developing new designs.	5	6	5	5	5	5	5	5.1
		5.6	6.0	4.8	5.0	5.6	5.0	5.0	

It is noticeable that user 3 also being the least experienced of the participant group (1 to 5 years) expressed the lowest rating in the reuse of design cases within the implemented viewpoint. His primary concern was if the information provided in the retrieved cases would help him to start a design. Because even how valuable the information provided is in searching for the initial design the justification for the selection of that case is still not with the information provided.

Another area to highlight is the response to question 1 with all participants agreeing that information provided in the viewpoint of reuse would be invaluable. In an industry that has high demographic changes occurring it is refreshing to know that tools implemented on a reuse viewpoint would provide a practical and useful tool for the industry. One user even commented: *"new people can go straight to the ten best jobs – superb"*.

The final section of the questionnaire was aimed at capturing the views of the users on the usability of the viewpoint software.

Usability

This part of the questionnaire was designed to capture the user's views on how useable the implementation was. The usability ratings are given in table 7.12. The split in the table refers to one question being on a different rating scale (1-4) as an assessment of the level of case used in the validation. A rating of 1 indicates 'not useful' and a rating of 4 indicates 'very useful'. In the validation for the ontology-based framework developed in chapter six an issue was raised to the level of the cases used in the validation study and as such an attempt has been made in this validation to avoid the same situation.

Table 7.12: Usability (average ratings).

		Rating 1 – 6							
Q	*Software Usability*	**User1**	**User2**	**User3**	**User4**	**User5**	**User6**	**User7**	
2	Were the instructions on using the CBR Tool made clear	5	5	6	5	5	5	5	5.1
3	How easy or difficult was it to use the CBR Tool	5	5	5	4	5	4	5	4.7
4a	Please rate the Navigation within the CBR Tool	4	4	5	4	6	5	5	4.7
4b	Please rate the Data entry	5	4	6	3	5	4	4	4.4
4d	Please rate the Ability to understand cases within the CBR Tool	5	5	5	4	5	5	5	4.9
4e	Please rate the Retrieving of design cases	5	6	6	5	5	5	5	5.3
4f	Please rate the Interpreting of similarity values	4	6	4	4	5	4	4	4.4
		4.7	5.0	5.3	4.1	5.1	4.6	4.7	

		Rating 1 – 4							
Q	*Software Usability*	**User1**	**User2**	**User3**	**User4**	**User5**	**User6**	**User7**	
4c	Please rate the Cases used	3	4	3	3	4	3	4	3.4

In this study the users rate highly the value and integrity of the cases and suggest that they reflected very closely the range of problems that are faced on a day-to-day basis for the design of special milling cutters. This provides the author of this research the verification of his choices of case for this part of the study.

The usability of the implementation is again rated positive. The instructions given to the users were rated highly i.e. the information provided by the author for the use of the implemented viewpoint. Second the CBR implementation allowed cases to be retrieved successfully and at an acceptable retrieval rate. Users 2, 3 and 5 were also the most positive in their responses with user 4 being the most negative about the usability of the implementation. His main complaint was that he was unable to understand the layout and operation of the CBR tool itself and thus this let his rating of the viewpoint be lowered. This is a limitation of the CBR software.

The usability of the system implementation of the viewpoint is very dependant on the software that the viewpoint is implemented on. The nature of the

interface was not as user friendly without a number of hours of use and development time. And hence if the user does not find it easy to grasp the interface then it will run up against problems. The analysis of the feedback in table 7.12 is immediately drawn to questions 4b and 4f. Question 4b relates to entering data into the system which requires several double-clicks in the fields in order for the field to become operable. This the users found frustrating especially users 6 and 7, being salespersons who work closely with customers suggest that this sequence of double-clicking would cause errors to be made. The notion of similarity for the users was not needed and hence the value is returned on the low side.
Navigating the tool was also an experience-based process and with the limited time available for the users to become experienced during the validation process is a suggestion for the low values to be obtained. In general the users found the implementation of the design reuse viewpoint easy to use despite problems mentioned above and with further development of the implementation these can be overcome.

The next section highlights the issues involved for the implementation of a Case-Based Reasoning tool on the sponsoring organisation and also examines the business benefit analysis of the implementation within the cutting tool industry.

7.5 IMPLEMENTATION ISSUES & BUSINESS IMPACT ANALYSIS

This section discusses the issues concerning the implementation of the aforementioned tool and considers the business impact of implementing a Case-Based Reasoning tool in the industry. The introduction of a new Information Technology system requires changes to occur in the organisation. Issues relating to this system introduction include maintenance of the system and implementation of the system. Also the management of the organisation must have seen some strategic need for the system in order to invest the time, financial and people resources for the implementation of the system. There will an impact on the business of the organisation.

7.5.1 Maintenance of the system

The case base will grow with time and the number of similar cases will increase but this cannot happen unless the organisation has ownership of the process and a quality procedure to ensure that the case base is kept up to date with relevant complete cases. This process cannot be left to chance: it requires management of the maintenance process.

Ownership

As with many organisational technology changes it requires an employee/s to claim ownership of the system. This is to keep the system running efficiently and to retrieve the appropriate cases with confidence for the users. Ownership requires the employee/s maintaining and updates of documents pertaining to the system, the running of performance checks, and the development of a user manual and keeping up with software updating. The consideration to which cases should go into the case base and those that shouldn't requires discussion with experts and an active policy for case inclusion should be decided upon.

Quality control

This is the maintaining of cases within the case base that are relevant at the current time. This means checking for cases that have become obsolete, this may involve a manual recording of what cases are retrieved until the process has some level of automation. The quality control process should involve checking for retrieval accuracy and consistency. Furthermore it should check for case duplication and case coverage. This should be done on a regular basis to suit the organisation. The procedures set up for this level of checking should be documented for others to implement if the owner/s of the system are unavailable. Also there needs to be procedures for the input of cases into the case base. As many of tests have proved of the system within this chapter the input format of the cases is very important. Standardisation of the textual and numerical inputs is vital to the success of the case base.

7.5.2 Implementation of the tool in the sponsoring organisation

The implementation of the system will have to be assessed by performing a feasibility study before approval to consider the technical issues, links with other systems and future use. Technical issues relate to the consideration of using another CBR software and user interface. There were a number of difficulties in using the CBR software used in the implementation of the viewpoint. This would require an assessment to choosing new software. The user interface would have to be changed to incorporate the views of the users including the off-site access by salespersons through the Internet.

The current software being used in the sponsoring organisation needs to be assessed for its compatibility and integration potential with software such as, Excel, Access, AutoCAD and other office based software. Particularly, integration with the CAD system to enable the designers to work more efficiently by not having to move away from their screens searching for information. Access through an existing network would be another prime consideration with security issues considered for authoring and accessing the case bases.

Considering the implementation issues for the future are potential changes in the sponsoring organisation with regards to its personnel, upgrade to 3D based CAD and other software & hardware. A plan of these future upgrades needs to be considered during the implementation planning both short term and long term. Another consideration for the future is the employee retention problem, if employees leave then the expertise in the development of these systems will be lost – this has to be accounted for.

7.5.3 Business impact Analysis

The implementation of a new system to the sponsoring organisation will cause an impact on the processes within the business. The impact of any change within the organisation, which affects the business no matter how small, should be analysed. Consideration to the organisational changes, costs & benefits of implementation and future trends in the industry should be made as a result of the change.

Change in the culture

Currently, the method for design searches is manual: searching through CAD design files by hand and through much iteration to find the right design. Also many of the individuals have their own ways of recording design information and systems (e.g. excel spreadsheets recorded manually) to find their own work, which is not often shared. This manual searching would be effected; a new routine for searching would be introduced together with the learning of a new system. This new technology to the demographic at the sponsoring organisation means that adoption of a system would be met with resistance.

Thus, the largest impact on the organisation is selling the system to the employees or end users of the system, as a change in their normal routines would be expected. There will be a change in the culture of the organisation. The change management literature suggests that individuals and organisations resist change (Carnall, 1995; LaMarsh, 1995). The emphasis would now be to integrate the system into the culture by minimising the resistance to the change. A number of factors to manage the change process can be considered to minimise the resistance.

> *Leader support* – by incorporating high-level management in the change/integration can ease the resistance to change. This was obvious at the sponsoring organisation as the author had the support of both the chief engineer and the general manager in the system development process.
>
> *Level of involvement/participation* – it is difficult for individual to resist the changes in they are part of the process. As the members of the design and sales department were experts in their job roles they were able to make a meaningful contribution to the system development process. This provided a commitment from the individuals and increased the quality of the system. The author actively encouraged this type of participation.

It should be emphasised that the employees of the sponsoring organisation consulted during the development of the system and more recently the validation and testing responded positively that the system would have a positive affect on the organisation (see section 7.4 within this chapter).

Change management in the sponsoring organisation

The technical processes and tools used to perform design tasks will be affected by the implementation of the system. The change would have to be managed by considering the socio-technical system (Robbins, 1997; Davis & Olson, 1984), which is, implementing of the system (the technology – tools, techniques, procedures, skills and knowledge) and a social system (the people and their interrelationships), as the task of design will change. Technology constrains the social system by shaping the behaviours required to operate it (Robbins, 1997). If the management ignore this then the change will fail. Therefore, considering the management of the change, as the organisation of groups rather than individuals will provide a successful change.

Cost of implementation

The costs of implementation require careful assessment. The tool provided here is only a prototype and hence further development work would be required in order to become operationally efficient. More cases need to be entered which require time and effort from the employees but prior to that: a change in the way the organisation currently organises and manages its design information and knowledge. This requires manpower to be assigned to create this level of change. An additional cost is the training on the system; to extend applications, maintain case base and using it to retrieve designs. Furthermore, the technical costs will be for the purchasing of the software and additional computing facilities if current technology does not support the programs. If integration is required between this and other applications run by the organisation then these will have to be programmed at additional costs.

Benefits of the implementation

The costs can be offset against the benefits that the system can bring both short and long term these need to be promoted by management. The efficiencies obtained in the design process, the increased interaction between salespersons and designers, information access to previously implicit design knowledge, faster initial quotation facilities, improved design searching, retrieval and reuse of the designs. Also the training of novices within the industry coming into the sponsoring organisation will be able to select an initial design to base their design work on. A greater level of confidence would be achieved with the system implementation reducing the amount of supervision required from the experts.

Link to the future business trends in the industry

The future trends were alluded to in chapter one of thesis (see sections 1.2.4 and 1.2.5). Those pertaining to this discussion are how and why will the customer to buy from us, and demographic changes in the market.

The implementation of the tool to the sponsoring organisation can improve quality, cost and design lead-times. This would provide selling power to the organisation when bidding for work from customers. By improving the quality of design – getting it right first time, this improves the impression of the organisation in the cutting tool industry. The operation costs of the organisation in terms of the design process would be affected for the better. Designs spend a majority of a design tasks searching for information to solve the design task. By providing a system that improves the searches and provides information would reduce the time taken to design, leaving the designer to get on with tasks that provide value to the design process. Hence the reduction in operating cost. Increasing the efficiency of the design process and the guarantee of delivery would bring customers to the organisation.

The demographic change in the market is probably the most worrying future trend for the cutting tool industry. The reuse of knowledge and the management of knowledge require an active policy by the organisation. Retaining its knowledge assets is of key importance of the future of the sponsoring organisation within the cutting tool industry. Implementing systems that capture and reuse knowledge such as the system described in this chapter are invaluable. Users of the system in the validation in section 7.4; commented positively that the tool provides information that is invaluable if individuals were to leave the organisation. Furthermore, they responded positively that this information would help in the future of cutting tool design. This section has described the implementation issues and business benefits to the sponsoring organisation of the CBR tool. The following section concludes the chapter with summary and key observations.

7.6 SUMMARY & KEY OBSERVATIONS

In section 7.1 the author captured the requirements of the reuse viewpoint. The main focus of these requirements was the need for a well-structured approach that provides a common understanding of the terms that are used for the search and retrieval of past designs. Also the viewpoint has to be both functional and easy to use so that the search, recall and reuse of the past designs would be accepted amongst the users identified in chapter 7.1.

Section 7.2 showed the development of the viewpoint for design reuse. A viewpoint of design reuse includes a set of descriptor terms and the associated domain knowledge. A set of descriptor terms were identified (having being mapped through an existing ontology) as appropriate for searching for past designs from the views of experts in cutting tool design. A viewpoint was constructed with the descriptors and domain knowledge. This viewpoint was then implemented onto a case base reasoning software.

The viewpoint was then implemented onto CBR software in section 7.3. The implementation was carried out through an iterative process. The interface development was described and the input of designs into the case base emphasised by use of examples. It was noted that continuity of the data entry into the case base was of utmost importance during the development of the case base. A pilot test of the viewpoint implementation indeed confirmed that the model could provide adequate retrieval of past designs.

In section 7.4 the viewpoint implementation was tested and validated against the criteria set out in section 7.1 with the research sponsors. The testing and validation showed that the viewpoint was both functional and usable as a tool to search recall and reuse past cutting tool designs in a structured approach.

In section 7.5 the author considered the implementation issues concerning the implementation of a CBR system into the sponsoring organisation. The business impact analysis of the implementation of the system was also considered for the sponsoring organisation.

The next chapter brings together the work described in this thesis and discusses in detail the implications of the work. The contributions of the work are highlighted. Also the research is concluded indicating how the research aim and objectives have been met. Finally, the areas for future work are addressed.

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CHAPTER EIGHT

Discussion, conclusions and future research

8.0 INTRODUCTION

The previous chapter illustrated the implementation of a design reuse viewpoint of a special purpose cutting tool design ontology described in chapter six. The ontology was the amalgamation of the work carried out in chapters four and five of this thesis. The literature review and results illustrated that the engineering design task is a complex and knowledge intensive task requiring several years of experience to be performed effectively. It also identified that the elicitation and capture of design knowledge was beset by the problems of communication and understanding between the experts and the novices in task orientated domains.

For this purpose a methodology to capture design knowledge was developed in chapter four. It was shown that this allowed novices to identify in a structured manner the key knowledge in cutting tool design tasks. In chapter five the KEN methodology was use to capture the knowledge required by special purpose cutting tool designers in terms of the internal, external and technological knowledge. This led to the identification of the function, behaviour, structure terms and the development of an ontology based framework for the representation of special purpose cutting tool design. From this ontology a viewpoint of reuse was extracted and implemented onto suitable software for the search and retrieval of past designs. It was shown through validation that the ontology represented special purpose cutting tool design knowledge and the implemented viewpoint of reuse was effective for the searching and retrieval of past designs.

This chapter discusses and concludes the research findings against the aim and objectives set out in chapter three, section 3.1. Therefore this chapter brings together the work described in this thesis and discusses in detail the findings of the work in section 8.1. The contributions of the work are highlighted in 8.2. The limitations of the work are discussed in section 8.3 followed by the addressing of areas for future work are discussed in section 8.4. And finally the conclusions from the research are drawn against the research objectives in section 8.5.

8.1 KEY RESEARCH OBSERVATIONS

This section summarises the key research observations considering the quality of the results from the each from work carried out to achieve the aim and objectives set out in chapter three, section 3.1. The key observations from each chapter are discussed in turn.

8.1.1 The capture & reuse of design knowledge

It was shown in the review of literature that the capture and reuse design knowledge is difficult to achieve due to the nature of the design task itself. It is observed that engineering design is a knowledge intensive and complex task that requires experience to be performed well and that the design task cannot be prescribed in an industrial situation. The nature of the special cutting tool design task requires a deep understanding of multidisciplinary technical issues that require capture. It was highlighted that there are not many studies to describe the design knowledge of special purpose cutting tool design.

It was observed that the design knowledge of cutting tool design is similar in nature to the manufacturing industry. Knowledge capture and reuse have been undertaken in this area to address the knowledge needs of the design office. It is observed that investigating the process in design and manufacturing has received the attention of many authors, however very few have undertaken an active participation role where the elicitor actually undertakes the tasks an expert would carry out on a day-to-day basis. By the elicitor actually undertaking the work of the expert, and armed with some knowledge of the domain, the real problems faced by the expert can be brought out. This allowed a clear statement of the problems faced by the elicitor to be made at each stage of the elicitation process, thereby leading to the elicitation of the most relevant knowledge. Wagner et al (2001) suggest that knowledge elicitation techniques (where knowledge engineers actively participate in the domain) capitalise on the idea that the knowledge engineer must become somewhat of an expert in order to translate the expert's knowledge and thus the interview may be treated as a tutorial where the expert delivers a lecture. Wagner et al also comment that this type of knowledge elicitation ensures the highest quality expert systems.

Two activities associated with knowledge capture have been identified in this research: knowledge elicitation and knowledge formalisation. A comparison between different knowledge elicitation techniques has been carried out. It is has been highlighted that there is a lack of techniques that allow the natural elicitation between a novice and an expert (Adesola, 2002). That is the current knowledge elicitation methods do not consider the interaction between the novice and expert in a language that often befits the design task i.e. the current techniques contrive to develop a dialogue. Therefore there is a need to improve this limitation to capture design task knowledge. A lack of familiarity with the terms and jargon used in cutting tool design would make the task specific knowledge capture very difficult for the novice. The knowledge engineer (the novice) and the expert will literally and figuratively not be seeing the same things, even when they are ostensibly talking about the same phenomena (LaFrance, 1990).

It was observed that expert systems for cutting tool design do not deal adequately with design knowledge. However, they take a very limited view on the knowledge required for the design. There is a need to understand the knowledge requirement and the nature and relationships of the knowledge better. LaFrance (1990) suggests that an understanding about how the expert's knowledge is structured and organised must be acquired.

Knowledge formalisation is now considered a modelling activity. The domain in question is modelled approximately creating a set of knowledge components that can be shared and reused. The common approaches to formalise knowledge have been identified and reviewed from literature. Amongst these the notion of creating an ontology for the conceptualisation of domain terms was selected. This is because an ontology provides a common language enabling the sharing and reuse of knowledge in a domain. This modelling approach requires the explicit conceptualisation of domain terms and the relationships between these terms in a natural language suitable for the domain. A functional approach to creating the ontology was chosen based on knowledge systemisation. This is because of the useful amount of examples that have been published illustrating the use of this technique and access to the developers. This ontology enables the common understanding of the domain between the experts.

The reuse of design knowledge was reviewed. It is observed that the two most common methods of reusing design knowledge are use of design assistants and the technique of case based reasoning. Case-Based Reasoning has been selected as the methodology for the implementation of design reuse in this research because it allows the user to use natural language, find the nearest matching problem description in the case base or even a set of similar problems and/or even ask several questions to confirm the matching problem (Watson, 1997). This functionality is useful for the special purpose cutting tool design domain. It is also observed that using the right viewpoint in the development of a design reuse system is vital. A viewpoint contains a description of the past designs and the associated domain knowledge in order to understand the past designs.

8.1.2 Knowledge = Expert – Novice (KEN): A novel methodology for Knowledge Elicitation

Participating in the design process and actively taking on design tasks similar to those of the expert requires a different approach to the capture of the design knowledge. The approach taken was to develop a methodology known as Knowledge = Expert – Novice (KEN). KEN refers to the difference between the expert and novice in solving a design task. The motivation for the development of the methodology was the difficulties faced by novices in the undertaking of the tasks of an expert designer. In each case the novice would ask the expert for assistance, knowledge would be exchanged from the expert to novice and following this interaction the novice would be able to solve the problem faced. It is argued that this is knowledge that an organisation should try to keep because it cannot be sourced from outside.

The use of KEN allowed the novice and expert to interact to solve the problems of the novice during the design task undertaken by the novice. It was shown through three cases in the cutting tool design domain that it provides a structured approach to the capture of knowledge. This structure was made possible by the use of templates or worksheets that recorded the interactions of the expert and novices. It was illustrated by the cases used that key task knowledge was obtained during the process and the participating experts verified these results. And in each of the case studies the novices within the cases were able to apply the knowledge gained through these interactions by trial and error successfully to the following tasks undertaken.

To show generality of the KEN methodology, KEN was used in a task-orientated domain such as cost estimating (Rush, 2002). It was found that KEN was applicable to the domain and that key task knowledge could be identified using the KEN methodology. The author realises that this is not an appropriate number of cases to base the judgement of generality but suggests that in another environment such as cost estimating the KEN methodology has identified key knowledge. In this way the method for recording of the identified knowledge has been shown to be flexible. For the design knowledge capture a worksheet was used and for the example from cost estimating a template was used. In both cases key task knowledge was identified. This is discussed further in the limitations see section 8.3.2. KEN is relevant for domains where a knowledge intensive task is taking place, which requires an expert to perform the task. The expert is needed to perform the knowledge elicitation. The types of domain that can use KEN are medical, architecture, or any other domain, which there is a need for a novice to learn the task or tasks.

Several benefits are accrued from using the KEN methodology. It is easy to use and highlights the process of novice/expert interaction in a structured approach. It overcomes the problems of domain language and communication beset in other techniques to elicit knowledge from a domain expert. First the novice has had some experience of the domain and secondly the expert can follow his responses and reveal to himself the problems of articulation of his knowledge. The KEN process also reduces the major disruption to the expert's work caused by other elicitation techniques where the expert would have to be taken out of the regular design environment and reveal knowledge about a case that has been developed for the purpose. In the case of KEN, the emphasis is on the novice being part of the design process and creating designs that are relevant to the business during the elicitation process. Also KEN helps to elicit detailed technical knowledge often only known to an expert. The experience of the expert enables him to recall the detailed technical characteristics of past designs that would solve the problem faced. Only an expert would be able to recall the level of detail required in the work he has carried out in the past. This will ensure that appropriate knowledge is attained and the disruption to the expert's work is kept to a minimum.

The key value added task was highlighted as the proposal stage of the design process as this is where the knowledge was acquired for use during the design task as described by the next section.

8.1.3 Knowledge requirements for special purpose cutting tool design

The utilisations of KEN in the design process provided the author with a structured, consistent format to record and document the knowledge. It was observed by the author that proposal forms were often incomplete at the proposal stage but still a designer was able to design a product based on these proposal forms. This highlighted that the special purpose cutting tool design task is knowledge intensive. It was also observed and experienced that the design issues involved were complex and required a vast amount of experience to enable a design to be produced. It was recognised by the author that it was here that designer made his initial considerations for the selection and subsequent reuse of past designs. The author was also able to highlight the amount of time required to search these designs.

Through using the matrix approach the assessment of problems faced by the designers with respect to the level of design involvement was possible. The enabler here was the identification of the industrial design process activities used at the sponsoring organisation. The design involvement was a qualitative categorisation developed between the author and several experts at the sponsoring organisation. This categorisation allowed an informal assessment from the point of view of the salespersons. This is then mapped to the design activities to give an indication of which level of design involvement instantiates a design activity. The design activities were mapped according to the design problems the designers need to address within those individual design activities. These interactions were rated and verified by both expert and novice designers.

This study allowed the three main categories of required knowledge to be identified. These are internal, external and technological. The designer's problems were then transformed into required knowledge and then categorised according to which of the three main categories that they pertained to. This provided the required knowledge for special cutting tool design at the proposal stage. There are certain categories that the standard product would belong to. For example (referring to figure 5.4, section 5.3.6), under the main category 'internal' there is a sub-category of 'products' it is here that the information regarding a standard product may populate these fields. The required knowledge on figure 5.4 is specific to the design of a special cutting tool and as such hold information regarding design considerations. The level of information in figure 5.4 is far more than required when selecting a standard tool from a catalogue – which is the current method by phone or internet.

The approach has been useful to identify designer's problems by questioning the designer of the problems he or she faces at the preliminary design stage. Asking questions is a basic linguistic strategy people have for communicating and, in particular, acquiring knowledge about the physical or social world (Mack & Robinson, 1992). This has been useful enabling the knowledge required by cutting tool designer to be acquired.

8.1.4 Developing an ontology-based framework for cutting tool design knowledge representation

The requirements for an ontology-based framework were obtained from the sponsoring organisation and the views of cutting tool practitioners in direct competitors of the sponsoring organisation. These highlighted the need for a set of "need to know" information providing a common language, which was structured and organised. The author developed an initial function, behaviour and structure view but found it too difficult to map to designs. This provided the author with a thorough grounding in the development of such models. A functional ontology was then developed following a methodology for knowledge systemisation. This provides a process for others to follow in the determination of subsequent ontology development. The ontology is in the form of functional hierarchies that lead to the design considerations that have to be made in order to design a cutting tool.

Validation

This research has validated and tested the ontology-based framework by a closed questionnaire and three cases studies. The questionnaire requested the validation participants to rate the terms in the framework (on a scale, 1 to 6) and represented the knowledge on special purpose cutting tool design completely. The cases studies were selected at random representing typical types of design task carried out in the design process. Three experts crosschecked the cases and the experts gave ratings for the given criteria. The purpose of the validation was to test the framework for completeness and to show that a typical design could be represented within the framework.

The framework was validated for completeness. All the participants agreed that the framework was complete and even included terms that they would never have thought of. The only real issues to arise were verb-noun descriptors given to two of the base-functions. This was raised by two of the participants rating the base-functions concerned as 'disagree' and 'slightly agree' and 'slightly disagree'. In each instance a discussion ensued to establish the error and a new term was agreed. Another issue raised by participant one in ratings for the 'ways of achievement' was that he was influenced by which way or ways he would choose to solve his design problems this resulted in him giving a 'agree' as an overall individual rating. It is widely known within engineering literature that determining the verb-noun pairings for functions is a difficult task to be carried out successfully and requires much iteration.

For the second part of the validation the experts agree that the framework represents cutting tool design knowledge with all three cases being rated fairly highly on the rating scale. There are differences in the way the experts have rated the cases but this is due to the different viewpoints to cutting tool design knowledge they have as they all do different jobs within cutting tool design. The results in terms of adequacy have been good with two out of three experts agreeing that the knowledge represented by the cases was of an acceptable quality. The one expert who did rate the ways of achievement low in his individual ranking suggested that he would not use some of the ways described in the ontology. His preference would be to choose a way that he was familiar with e.g. a milling or turning way. The author could only reflect that this was due to personal preference and was brought about by how the expert prefers to solve problems in the domain.

Observing the results based on coherence, it was demonstrated by the experts that they felt the knowledge represented was both logical and consistent throughout. They concede however that this would only occur if all parties were to complete the tables as honestly and in as full of information as possible. There would have to be some procedures to help individuals fill out the tables in order to show the consistency required for the knowledge representation. This suggests that the framework's usefulness in a practical situation may be affected by lack of motivation of the users.

The completeness of the case studies was rated as 'agree' by the experts. The case studies provided enough knowledge and information to carry out a design of similar nature. However, there are some missing items that were not available at the proposal stage. Again this shows that if the information is not provided in the first place than completing the values in the framework would be difficult. The framework provides a guide as to the level of information is required for effective cutting tool design, which would be useful to a novice or other departments of the sponsoring company.

In summary the ontology-based framework provides a structured representation that illustrates the design considerations that are required to design a special purpose-cutting tool. This would be helpful for both expert and novice designers to assist them in the design tasks.

8.1.5 Implementing a viewpoint of design reuse

The requirements for a viewpoint of design reuse were captured from industry and academic literature. A viewpoint of design reuse was developed in this research. It is observed that a viewpoint must contain a description of the domain and the appropriate set of domain knowledge. The descriptor terms were derived jointly with an individual MSc project student as described in chapter six. The domain knowledge was captured and analysed by the author of this research during participation and subsequent visits to the sponsoring organisation using a wide variety of sources. This was then implemented onto suitable CBR software by mapping the descriptor terms (derived concepts) into fields on the software. Then domain knowledge was used to populate the case base as attributes of those descriptor terms. The designs were then analysed by the checking for the attributes and extracting values to correspond with the attributes. These values were entered onto the case base as individual cases.

Validation

To test this viewpoint seven experts from the sponsoring organisation used the prototype. Five of these experts were designers including one novice and two salespersons. Five cases were used to test the data extraction from the design documentation. The user to retrieve a design then entered this data in the form of values for the attributes. Two of the cases were on the case base and the remaining set of three were chosen at random but not included in the case base. This was to see if a similar drawing would be retrieved that could be used for that design documentation. The terms extracted and entered onto the case base were recorded as well as the subsequent similarity values returned for analysis of the results. Finally a questionnaire asked through closed questions which required the users to rate from 1 to 6 (strongly disagree to strongly agree) the effectiveness of the searching, recall and reusing of design cases. The usability of the software was also questioned in a similar manner.

In a comparison of the novice and expert designers it was observed that the novice attempted a rather through search and extraction of the design terms before any input was made to interrogate the case base. The expert on the other hand found the critical values in his opinion and used those to search the case base. Upon the return of the values he would enquire again at the documentation and extract values if he required any confirmation that the designs returned were of any use. In tests for similarity on the cases it was observed that it was not possible with this case base (not enough cases) to identify a very similar match however the expert was able recognise those of the cases retrieved where there were parts of these design that could be used. It was also interesting to note the expert was not judging this on the similarity values obtained but rather on merit of the returned cases. Furthermore there are instances when the expert is able to extract information from the design documentation that does not appear on the documentation provided. There are two possible reasons for this: he remembers characteristics about the design previously or he is able to use experience and extrapolate a set of values for entering on the case base and hence performing a search.

The viewpoint was tested for its effectiveness in searching for designs. The users stated it was effective. The major point of discussion was the need for the tool types requiring further expansion. Two of the respondents rated this as slightly agree, four rated it agree and one strongly agree to the attributes being appropriate for this viewpoint. The attributes in this case are the type of domain knowledge in the system.

In the next section of the validation the viewpoint was tested for its effectiveness in recalling past designs. The previous paragraph reflecting the operations of the expert and novice are taken into consideration here. The respondents individually agree that the viewpoint is effective for past design recall. The only concern from the respondents was whether the viewpoint provides a common understanding of cutting tool design and whether the viewpoint would allow better quotations to be made. The latter is difficult because cost information is not recorded on the designs and hence would be difficult to implement into the case base. The addition of cost information could be considered as a future expansion of the existing system, see section 8.4. The former is a concern that users would have to be constrained in the terminology that is used when inputting the data into the case base. Again this a possible future improvement in the tool, see 8.4.

The viewpoint was also tested for its effectiveness for the reuse of past designs. All respondents agree that it is effective. The greatest concern from the novice was that there were indications other than the similarity values to help him decide which case to select in reuse. As discussed in a previous section the novice was not able to select a design from the returned cases.

The final section required the users to test the usability of the software. The views ranged from slightly agree to agree. The nuances of the software were initially hard to overcome by the users and hence its usability ratings were low. This is discussed in the limitations, section 8.3.5.

Summarising the testing phase on the implementation of the design reuse viewpoint demonstrated that the viewpoint was an effective description for the extraction, search, recall and reuse of past design cases in special purpose cutting tool design.

8.2 RESEARCH CONTRIBUTIONS

This section highlights the contributions made by undertaking this research work. This research has contributed significantly to the understanding of the role and extent of design knowledge in special purpose cutting tool design. It was identified that special purpose cutting tool design knowledge is complex and knowledge intensive and therefore difficult to capture without the active participation of an individual. The knowledge required by special purpose cutting tool designers was identified and formalised into an ontology-based framework for its representation and the research highlighted the development of a viewpoint of design reuse that allowed cutting tool designers to search and retrieve appropriate past designs. The contributions to knowledge identified during this research are as follows:

- This research identified that special purpose cutting tool design is complex and knowledge intensive and requires a vast amount of experience to be performed efficiently and has identified that it is difficult for a novice to perform the design without interacting in the domain;

- This research has identified and developed a methodology for the capture of cutting tool design knowledge. Knowledge = Expert – Novice (KEN) provides a structured approach for the interaction between an expert and a novice. This is a novel Knowledge Elicitation technique where the knowledge elicitor participates in the domain actively.

- The research has identified that the key stage in the special purpose cutting tool design process is the proposal stage and that the knowledge required by designers at this stage is a combination of internal, external and technological knowledge

- Analysis of the knowledge required by designers at the proposal stage has resulted in the development of a functional ontology for the representation of special purpose cutting tool design. A viewpoint of design reuse was successfully extracted from the ontology to demonstrate its effectiveness in searching and reusing past designs.

8.3 RESEARCH LIMITATIONS

8.3.1 Research design

The method chosen for the research was determined by the nature of design knowledge. The knowledge of design resides in the minds of the design experts and as such it is tacit, requiring a qualitative approach to interact with designers about the knowledge within the process. The qualitative approach leads to forms of interpretation and bias: it is therefore difficult to replicate the results in this research completely.

The policy of the Engineering Doctorate scheme dictates that the Research Engineer is to work closely with a sponsoring organisation and that the sponsoring organisation be used for case studies. Therefore the selection of the case study organisation was defined prior to the researcher undertaking the research.

The approach taken to explore the role and extent of knowledge at the sponsoring company was to actively participate in the design process. The author spent six months with the sponsoring organisation. This participant observation method can involve bias related to a prolonged stay in the domain of investigation. There are three issues here: The respondent and reactivity bias will be reduced as the author begins to get accepted and as the trust develops between the author and the respondents, the respondents are less likely to give biased information. The third issue is that the bias of the author may begin to develop either positively or negatively. The former is the problem of 'going native' and the latter is the development of antipathy. Overcoming these biases or subjectivity is achieved by the author (observer) retaining openness, reflexivity and independence in the participation.

With openness, the observer should remain open to the discovery of novel or unexpected issues that may come to light as the study progresses. Reflexivity refers to the observer taking a reflective and empathetic stance in striving towards an understanding of the respondent's point of view. The observer should take into account of, rather than striving to eliminate, their own affects upon the behaviour of the respondent. Also the observer should remain independent; the observer must not be constrained by pre-determined goal-set, mind-set or theory.

As a result of the above it is difficult to assess whether another researcher could obtain the same results as the author. However in order to provide a audit trial to enable another researcher to follow the data capture of the author the following were attempted to provide reliability and validity in the data capture:

- The author interacted with several members of the domain to obtain a member view;
- The informal discussions were recorded in a notebook;
- The author used several sources of data: members of the domain, academic and industry based literature with examples kept for record of activity;
- The recording of the design task undertaken including what decisions were made.

8.3.2 Knowledge = Expert – Novice (KEN): A novel methodology for Knowledge Elicitation

The KEN methodology relies on the novice being able to realise that he or she is stuck or facing difficulties. However, perhaps the most important of these is the production of a design by the novice that is not correct – how does a novice identify this? Or how can the methodology be adapted to provide this level of support? These questions have not been answered in this thesis as the methodology has not been advanced to incorporate the cognitive issues involved in the novice deciding this level of question. It is however the opinion of the author that it is a manifestation of the background of the novice that would decide the answer to such a question.

The follow on from this area is the inability of the novice to be able to ask relevant questions about the problem due to lack of knowledge about the terminology of the domain. This would affect the level of the knowledge obtained from the expert – is it the right knowledge to solve the problem faced by the novice? The check for the novice in this situation is to apply the knowledge given by the expert on a similar problem; therefore the iterations required for the KEN process depend on the level of questions by the novice. The more iteration required in the KEN process the longer the time taken for the novice to solve the problem.

It follows then that the knowledge elicited will depend on background of the novice and expert. Different experts will give different knowledge to the same problem being solved according to their point of view in the domain. The novice has to interpret this knowledge feedback and this brings the issue of subjectivity. Theoretically it might be possible for two or more novices to be used to solve the same problem and a range of knowledge can be obtained for different type of questions and different responses. The time taken and resources needed to undertake a multiple novice interaction would make it virtually impossible in an industrial environment. However, if this knowledge is recorded and used again a second novice may not find it useful, thus having to repeat the exercise.

8.3.3 Knowledge requirements for special purpose cutting tool design

The matrix approach developed for the knowledge capture depends on the author's participation in the design process using KEN and as such is prone to the same interpretation bias that is discussed in section 8.3.2. The first step in the process is to learn the design process and identify key value added tasks in the design process. The prolonged and persistent association of the author in the design process reduces the interpretation bias in this case.

Using just two expert salespersons and two designers (an expert and a novice) in the study could have affected the richness of the knowledge obtained. The time and resources available to the author were a limiting factor in the choice of participants. It may have been better to include the other members of the organisation. Accompanying the salesperson on visits to customer sites would have provided a richer view of the problems faced by salespersons on the completion of the forms.

The limitation of the scale of the design process is also an issue. If the scale of the design project is large then the management of the matrices will become a problem in a paper-based form. In a more complex environment such as the design of an aircraft, this level of analysis would become a problem due the amount of components that are involved in the design of an aircraft. This would require the decomposition of the design process and activities to use the matrix approach.

8.3.4 Developing an ontology-based framework for cutting tool design knowledge representation

An initial function-behaviour-structure model was developed to gain an understanding of the development of such models as their derivation is beset with problems of identification of the terms. These are all interpretations by the author, which were obtained from a variety of sources aiding the understanding gained by the author while participating in the process, and studying of the academic and industry based literature. Because of this interpretation factor it would be difficult to replicate. To reduce the amount of interpretation from the author two experts and one novice (outside of the cutting tool design) were asked for their interpretations of the terms function, structure and behaviour. These were recorded and used as the basis for the development of the functional ontology. The functional ontology was developed by identification of base-functions, design considerations and ways of achievement. Throughout the development of the ontology the author kept an extensive record of the activities carried out during the study reducing the author bias so that another researcher could follow the work carried out.

Although this process of ontology development has been successfully carried out for special purpose cutting tool design at the sponsoring organisation it remains to be seen whether the ontology would applicable to the rest of the cutting tool design industry. The model has not been tested in any industry competitor. To reduce this threat to the validity of the model the author incorporated the views obtained from the industry competitors for the need for a common natural language representation of cutting tool design. The validation process carried out demonstrated that the ontology provides a complete view of the knowledge in special purpose cutting tool design.

There was an issue pertaining to the level of technical demand on the second case study during the validation. This respondent bias is from experts with a range of 25 to 30 years experience of cutting tool design. Thus their views on the level of the designs used in the case study reflect the view that for them this would be a non-complex case. However the author argues that for a novice this would be a complex design task due to the nature of the cutting tool. In hindsight this is a failing on non-availability of a design novice in the organisation at the time of validation.

8.3.5 Implementing a viewpoint of design reuse

The viewpoint chosen for this research is the viewpoint of several designers at the sponsoring organisation. The descriptor terms used in the "reuse" viewpoint were derived from the views of cutting tool designers and therefore subject to some bias. Multiple experts with different backgrounds validated the terms in the ontology and thus reduced the bias of the author in developing the terms.

Also using case studies that have been designed before may bring a certain amount of responder bias to the process. In these cases it was likely that the users of the viewpoint in the validation had seen the design cases before. However as there were seven members in the validation user group then this bias was reduced. It can therefore be argued that this viewpoint is important for the reuse of special cutting tool design knowledge.

The interpretation of the author in the collection of the domain knowledge was another limiting factor. The author in the collection and analysis of the domain knowledge referred to wide range of materials. These included the use of both academic and industry based literature, the catalogues from within the cutting tool industry and knowledge obtained through interactions with experts during participation in the design process. Each of these sources was recorded in journal notes, examples of the designs undertaken taken by the author to provide an appropriate trial of evidence. The analyses of fifty designs were used by the author to develop his knowledge of the domain and therefore a level of interpretation is involved in the process. The expert designers were able to verify that this was a representative sample of the type of design work carried out in the design process.

The implementation of the viewpoint of design reuse was tested in the sponsoring organisation successfully including expert designers and salespersons; it has not been possible to test the viewpoint on a wider level within the cutting tool industry. The selection of the software to implement the viewpoint was a choice by the author based on the cost, availability and ease of use of the interface and case base. There were no technical issues related in the selection of the software. The prototype could have been better developed if the author had a better grasp of programming skills to improve the user interface.

The selection of the CBR software provided the users with an initial problem and its interface was not received well by the users. This interface could have been improved by the author with the further availability of resources. The similarity metric used in the implementation of the viewpoint was the default settings on the software. Therefore this showed no priority to the attributes that were being searched for. Weighted values for the descriptor were extracted by (Hodges, 2002) could have been used in this case. It can be argued that this did not provide a useful guide in the similarities obtained. Also the small number of cases could have influenced the retrieval of the designs. In terms of time and resources available for this research the analysis of cases, entering cases onto the case base was a factor in the number of cases utilised. The cases used to test the model were selected at random to ensure that the cases were representative of the domain.

8.4 FUTURE RESEARCH

Knowledge = Expert – Novice (KEN) requires further testing in other design industries to show that it is a generic tool for the capture of design knowledge. Guidelines for the use of the methodology can be developed based on further use of the methodology in other domains. This methodology should be developed as a tool for the training of novice and experts in industry. The investigation into the how a novice realises they are finding difficulties, that they are stuck or have a solution that is not correct should be carried out. The result would be the development of a guide to assist novices in deciding upon these issues.

This research has explored the domain of special purpose cutting tool design knowledge and as such has developed a semi-formal representation of the domain with an ontology-based framework. The author has captured in depth within the sponsoring organisation the knowledge of several types of cutting tool, design and sales views and thus the ontology is representative of special purpose cutting tool cutting tool design. It was observed that in all three organisations (Widia Valenite, Kennametal and Sandvik) that there are similar processes however the subtle differences of handling knowledge in each organisation remain to be investigated. The author also sees benefits of the functional ontology approach in other design domains were an explicit representation of the design considerations would be of great benefit to expert and novice designers alike.

The Case-Base Reasoning approach demonstrated in this research is only a prototype to illustrate the ability to search for designs using a natural language set based the language of the domain experts. This would include the development of a custom similarity metric that would be of benefit to the searching capability of the case-base. Also the integration with other design automation software would be a possible benefit to the designer. The designer requires a system that can run alongside his existing software and hardware capabilities e.g. a CBR system that runs on the CAD terminal. The author believes that the future integration of cost information to the existing CBR system would be of great benefit to an organisation such as the sponsoring organisation. To control the data entry on the software an interface that provides a series of drop down menus would be of advantage to provide consistency in the case representations.

8.5 CONCLUSIONS

This section concludes the research findings and demonstrates how the objectives and the aim of the study were achieved. There are six objectives for this research; each one is now taken individually in turn and the conclusions drawn for each will be highlighted.

In the first objective the author was to carry out a detailed review of the state of the art in the capture and reuse of design knowledge, the author identified that:

- There is very little research concerning the role and extent of knowledge used within the special purpose cutting tool design industry, however knowledge in design has been investigated in other domains such as manufacturing and on the shop floor;
- There are existing expert systems for cutting tool selection which rely on parameter matching, this limits their view of the knowledge requirements for design;
- There is a need to develop a knowledge capture methodology for design tasks as there is a lack of techniques that allows the recording of level of interaction required in the design process;
- An ontology-based approach would be a viable method of obtaining a natural language conceptualisation of the domain of special purpose cutting tool design to enable the sharing and reuse of knowledge amongst the communities in the domain;
- The most suitable approach for design reuse in this research is case based reasoning and that the method of retrieval should be based on attribute-value pairs.

For the second objective the research focused on the development of a methodology to capture special purpose cutting tool design knowledge by novice participation in the process. The author identified that:

- Design of special purpose cutting tools is knowledge intensive. It uses both formal and informal knowledge requiring a "sitting with Nelly" approach to teach design;
- KEN could affectively capture cutting tool design knowledge in a structured manner. It is also applied to the Cost Engineering domain effectively to check its relevance for other task domains.
- KEN can identify the informal knowledge required in the design, which is not known to the novice.

The third objective was to participate in the existing design practice within an industrial environment to explore the nature and extent of the knowledge requirements of a designer during the design process. The author has identified from this participation that:

- The information provision at the proposal stage of the design process is insufficient and requires that the designer spend a vast amount of his time searching for missing information;
- The knowledge of the designer is multi-faceted requiring several different types of formal and informal knowledge including internal, external and technological.

The fourth objective within this research was to develop a special purpose cutting tool design ontology for the representation of the knowledge required by designer in the domain. To achieve this objective the author identified:

- The base-functions and meta-functions for a special purpose cutting tool system by using a Knowledge Systemisation methodology;
- The ontology was developed and validated using design experts and salespersons from special purpose cutting tool design and it was shown that it represented a complete formalised structure of the design knowledge required in special purpose cutting tool design.

The fifth objective in this research was to develop a viewpoint of the ontology for effective reuse. For the achievement of this objective the author:

- Proposes that a viewpoint of design reuse requires a description of the domain and an equivalent set of domain knowledge in order to perform appropriate searches and retrieval of past designs;
- Captured domain knowledge to populate the description of the domain including the views of both salespersons and designers.

The final objective was implementing a "reuse" viewpoint of the ontology in a suitable software environment. To achieve the final objective the author:

- Tested and validated the viewpoint, demonstrating that it provided an effective approach for the extraction of information from design documents for both expert and novice designers;
- Tested and validated that the viewpoint allows a designer to search, retrieve and reuse appropriate designs;
- Has assessed the issues related to the implementation of the CBR system on the sponsoring organisation including the maintenance, and business impact.

In conclusion the research has successfully developed a methodology to capture the cutting tool design knowledge and an ontological framework to represent this domain knowledge. The cutting tool design ontology is then analysed to develop a 'reuse' viewpoint for implementation within a case based reasoning environment. Expert and user validation at different stages of the study proves that the research has achieved its stated objectives and the aim. The thesis has also identified main areas of limitations of the research and has proposed research areas for the future.

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APPENDIX A

Knowledge = Expert – Novice (KEN): A novel methodology for Knowledge Elicitation

A1 QUESTIONNAIRE FOR INVESTIGATING INDUSTRY DESIGN PROCESSES

General

1. Where are the main sites of organisation located?
2. What is their function?
3. How does the UK operation sit within this organisation?
4. Who are you're your main competitors?
5. What is the level of design technology within the organisation?
6. Are you linked electronically to other sites? Can you share CAD models?

Section one: Design process

1. Describe how the design activity organised?
2. How many designers are needed on the design process?
3. On average how long would it take for a component to be designed from original enquiry to manufacture?
4. Describe the factors or drivers that contribute to this lead-time.
5. At what stage in the design process, would knowledge of manufacturing be taken into consideration?
6. What initiates involvement of the design team?
7. What are the steps taken in the design process?
8. Do you reuse any past designs? If so, describe the types of modifications that could be applied an existing design to meet the new requirements?
9. What design knowledge and design rationale (why the cutting tool is design in a particular way) is used again for decision making?
10. Are there any procedures for recording and documenting the decisions undertaken to achieve a particular design?
11. Is there any design information recorded on a computer system?

Section Two: Customer interaction

1. Is there a quality check for designs prior to manufacture?
2. What form of quality check is performed?
3. Does Kennametal manufacture the cutting tool designs?
4. What knowledge of the manufacturing process is used in the design of a cutting tool?
5. Is regular feedback from manufacturing taken into consideration in the design process?
6. How would this feedback be passed back to the design team?
7. Who are the major customers?

8. Describe the type of interaction that is undertaken with customers?
9. What feedback is given by the customer on how well the cutting tool performed in the particular application?

Section Three: Experience level for cutting tool design

1. How do you recruit new designers?
2. How are new engineers trained to design cutting tools?
3. How is knowledge and experience transferred to new engineers?
4. What level of experience is required to design a special tool?
5. Are there specialists in particular areas of the design, i.e. inserts, turning tools or milling cutters?

Section Four: Knowledge systems

1. Do you know of expert or knowledge based systems?
2. Explain your understanding of the term 'knowledge'. Describe what you would term knowledge when dealing with the design of cutting tools?
3. What knowledge is there in a cutting tool design? Can you give examples?
4. Do you capture knowledge at Kennametal? If so, to what extent?
5. What knowledge management activities is Kennametal undertaking?
6. How much knowledge is involved in the design process?
7. How much time is spent looking for design information?
8. Describe the differences between a novice designing a component and an expert designing a component

A2 TRANSCRIPT FOR DESIGN CASE THREE (FROM HODGES, 2002)

The first KEN loop leads to the elicitation of the information relating to the component's material. The elicitor describes his problem in the following terms:

Description: *"Looks like a grooving task has to be performed. I do not know the material to be machined."*

This logically leads on to a straight question to the expert:

Question: *" What material has to be machined here?"*

The expert applies his knowledge and assumptions and makes the following reply:

Reply: *"This is some king of spanner shaft so it is going to be steel"*

Implicit in this reply is the elicited knowledge:

Knowledge: *"Spanner shafts are likely to be made from steel. Assume that the* *material to be machined is steel."*

Having performed this elicitation loop the elicitor concludes that he has insufficient information to search for the design solution. He therefore engages in another elicitation loop.

He decides that he does not know how the required form to the grooves is to be produced and formulates the following description of the problem preventing him from identifying the correct design solution, thus:

Description: *"I am wondering how the 30° form to the grooves can be produced?"*

This translates to the straight question to the expert:

Question: *"How is the 30° form to the teeth produced?"*

The expert applies his knowledge and assumptions and makes the following reply:
Reply: *"Use a triangular insert and put a 30° form on the front."*

Implicit in this reply is the knowledge:

Knowledge: *"The form required on a machined part can be produced by replicating that same form on the insert."*

At this point the elicitor knows that the insert has to be triangular and has to have a prescribed form. His knowledge, obtained up to this point through book and video study of the domain of cutting tool design, and through the KEN interactions for design problems undertaken prior to this current design problem, permits the assumption that the appropriate insert can be one of two types. It can either be a TNEC or a TPEC insert. The former is a triangular insert with a negative geometry and the latter a triangular insert with a positive geometry.

The next obstacle to recalling the design solution relates, therefore, to the specific geometry details beyond that of the form on the insert. He formulates the problem in his head in the following way:

Description: *"I know the form of the insert, but what about the other geometry details?"*

With this in mind and the notion that the appropriate insert should be one of either a TNEC and a TPEC insert, he interrogates the expert, thus:

Question: *"Should a TNEC or a TPEC insert be used?"*

The expert replies:

Reply: *"Use a TNEC32 because you are cutting steel."*

The elicitor has already learned from prior study that negative geometries on inserts produce stronger cutting edges and therefore the knowledge is elicited:

Knowledge: *"Using an insert with a negative geometry will provide the strength required for machining steel."*

Having completed these three elicitation loops, the elicitor is able to conclude with the statement of what should be looked for in recalling the design solution:

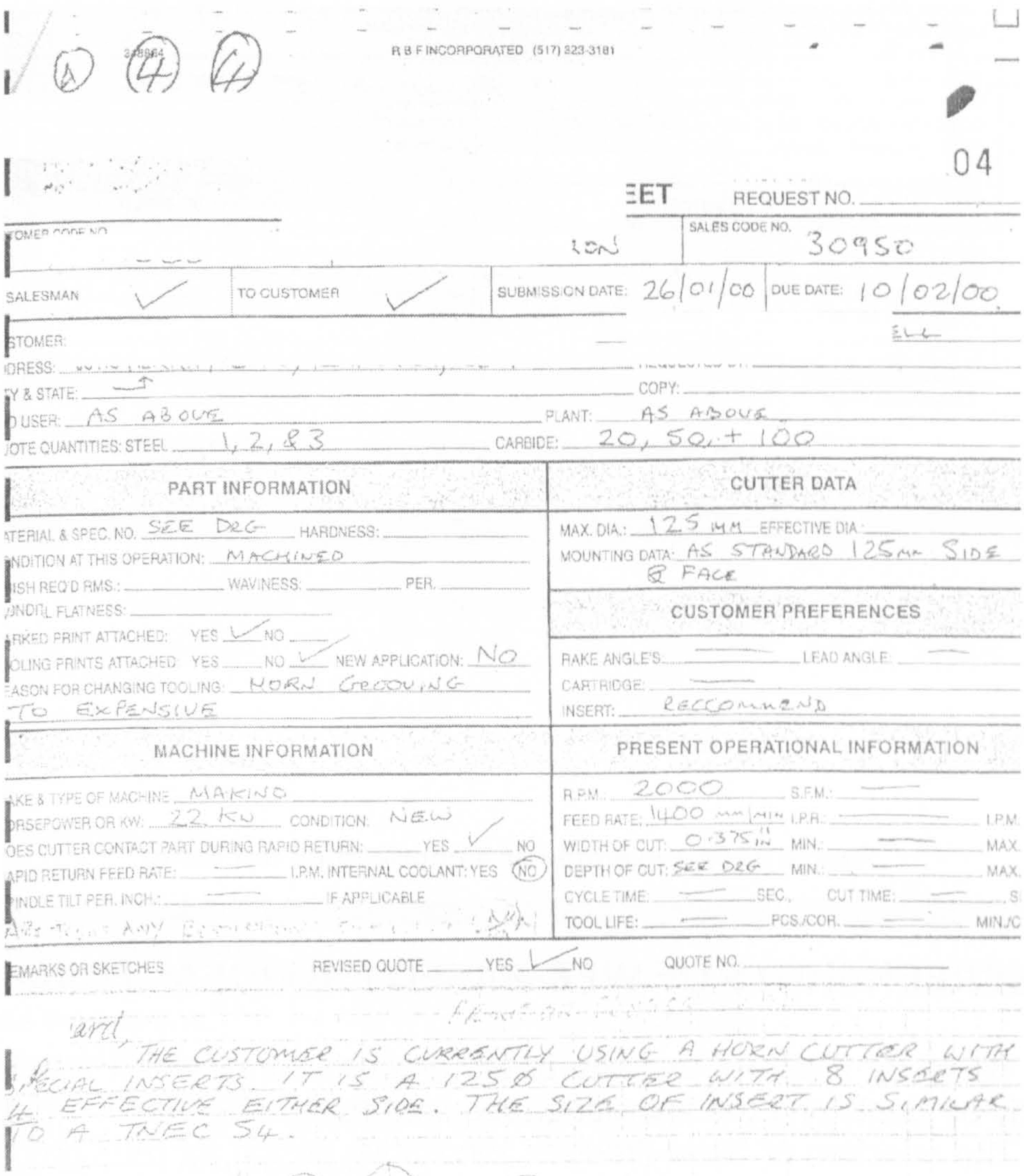
Problem Solution: *"Look for a special grooving insert with a 30° form and a negative geometry."*

APPENDIX B

Knowledge requirements for special purpose cutting tool design

B1 EXAMPLES OF PROPOSAL FORMS

Figures B1 & B2 present examples of a 'well-filled' out proposal form, and correspondingly a 'poorly' filled out form respectively.



R B F INCORPORATED (517) 223-3181

04

...EET REQUEST NO.

SALES CODE NO. 30950

SALESMAN ✓ TO CUSTOMER ✓ SUBMISSION DATE: 26/01/00 DUE DATE: 10/02/00

...STOMER:

...DRESS:

...Y & STATE: COPY:

...D USER: AS ABOVE PLANT: AS ABOVE

...OTE QUANTITIES: STEEL 1, 2, & 3 CARBIDE: 20, 50, + 100

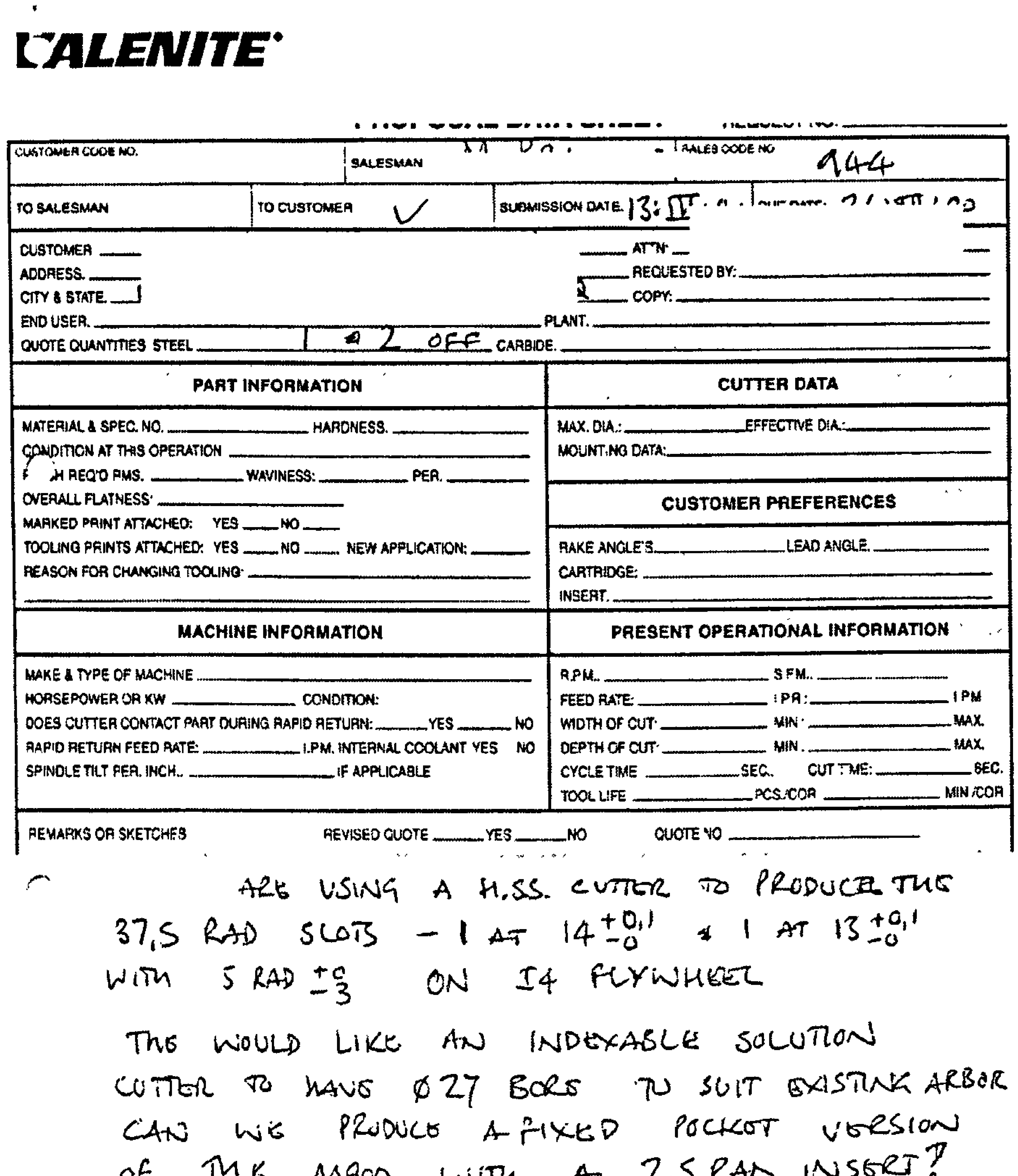
PART INFORMATION	CUTTER DATA
...TERIAL & SPEC. NO. SEE DRG HARDNESS:	MAX. DIA.: 125 MM EFFECTIVE DIA.:
...NDITION AT THIS OPERATION: MACHINED	MOUNTING DATA: AS STANDARD 125MM SIDE & FACE
...ISH REQ'D RMS.: WAVINESS: PER.	
...NDR... FLATNESS:	CUSTOMER PREFERENCES
...RKED PRINT ATTACHED: YES ✓ NO	
...OLING PRINTS ATTACHED: YES NO ✓ NEW APPLICATION: NO	RAKE ANGLE'S: LEAD ANGLE:
...EASON FOR CHANGING TOOLING: HORN GROOVING TO EXPENSIVE	CARTRIDGE:
	INSERT: RECCOMMEND

MACHINE INFORMATION	PRESENT OPERATIONAL INFORMATION
...KE & TYPE OF MACHINE: MAKINO	R.P.M.: 2000 S.F.M.:
...RSEPOWER OR KW: 22 KW CONDITION: NEW	FEED RATE: 1400 MM/MIN I.P.R.: I.P.M.
...OES CUTTER CONTACT PART DURING RAPID RETURN: YES ✓ NO	WIDTH OF CUT: 0.375 IN MIN.: MAX.
...APID RETURN FEED RATE: I.P.M. INTERNAL COOLANT: YES (NO)	DEPTH OF CUT: SEE DRG MIN.: MAX.
...INDLE TILT PER. INCH: IF APPLICABLE	CYCLE TIME: SEC., CUT TIME: S
	TOOL LIFE: PCS./COR. MIN./C

...EMARKS OR SKETCHES REVISED QUOTE YES ✓ NO QUOTE NO.

THE CUSTOMER IS CURRENTLY USING A HORN CUTTER WITH SPECIAL INSERTS. IT IS A 125 Ø CUTTER WITH 8 INSERTS 4 EFFECTIVE EITHER SIDE. THE SIZE OF INSERT IS SIMILAR TO A TNEC 54.

Figure B1: An example of a well-filled out proposal form.



VALENITE

CUSTOMER CODE NO. | SALESMAN | SALES CODE NO 944

TO SALESMAN | TO CUSTOMER ✓ | SUBMISSION DATE 13.II

CUSTOMER

ADDRESS

CITY & STATE

END USER

QUOTE QUANTITIES STEEL 2 OFF CARBIDE

ATTN

REQUESTED BY:

COPY:

PLANT:

PART INFORMATION

MATERIAL & SPEC. NO. ____ HARDNESS ____

CONDITION AT THIS OPERATION ____

FINISH REQ'D RMS. ____ WAVINESS: ____ PER ____

OVERALL FLATNESS ____

MARKED PRINT ATTACHED: YES ____ NO ____

TOOLING PRINTS ATTACHED: YES ____ NO ____ NEW APPLICATION: ____

REASON FOR CHANGING TOOLING ____

CUTTER DATA

MAX. DIA.: ____ EFFECTIVE DIA.: ____

MOUNTING DATA: ____

CUSTOMER PREFERENCES

RAKE ANGLE'S ____ LEAD ANGLE ____

CARTRIDGE: ____

INSERT ____

MACHINE INFORMATION

MAKE & TYPE OF MACHINE ____

HORSEPOWER OR KW ____ CONDITION:

DOES CUTTER CONTACT PART DURING RAPID RETURN: ____ YES ____ NO

RAPID RETURN FEED RATE: ____ I.P.M. INTERNAL COOLANT YES NO

SPINDLE TILT PER. INCH ____ IF APPLICABLE

PRESENT OPERATIONAL INFORMATION

R.P.M. ____ S.F.M. ____

FEED RATE: ____ I.P.R.: ____ I.P.M.

WIDTH OF CUT ____ MIN ____ MAX.

DEPTH OF CUT ____ MIN ____ MAX.

CYCLE TIME ____ SEC. CUT TIME: ____ SEC.

TOOL LIFE ____ PCS./COR ____ MIN./COR

REMARKS OR SKETCHES REVISED QUOTE ____ YES ____ NO QUOTE NO ____

ARE USING A H.S.S. CUTTER TO PRODUCE THE 37,5 RAD SLOTS – 1 AT $14^{+0,1}_{-0}$ & 1 AT $13^{+0,1}_{-0}$ WITH 5 RAD $^{+0}_{-3}$ ON I4 FLYWHEEL

THE WOULD LIKE AN INDEXABLE SOLUTION CUTTER TO HAVE Ø27 BORE TO SUIT EXISTING ARBOR CAN WE PRODUCE A FIXED POCKET VERSION OF THE M900 WITH A 2,5 RAD INSERT?

Figure B2: An example of a poorly filled out form.

B2 SCREENSHOTS OF WEB-BASED PROPOSAL FORM

Figures B3 to B4 illustrate the web-based proposal form, which resulted from the study of identifying the knowledge required for special purpose cutting tool design. The selection of "New Product: Innovative design for the Company" will select the page form page as illustrated in figure B4. It is here that the user can enter the values and send the form.

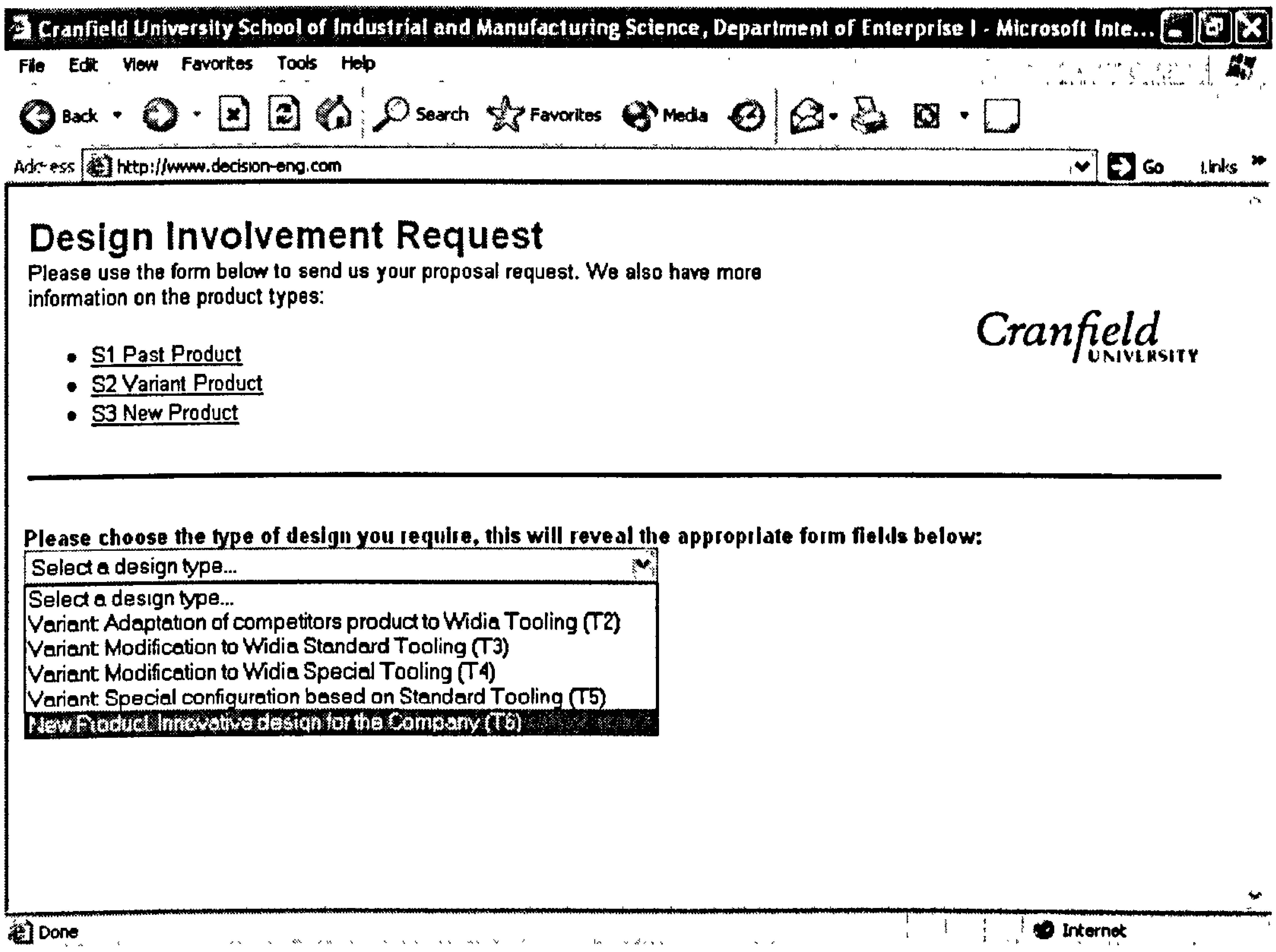


Figure B3: Homepage for web-based proposal form.

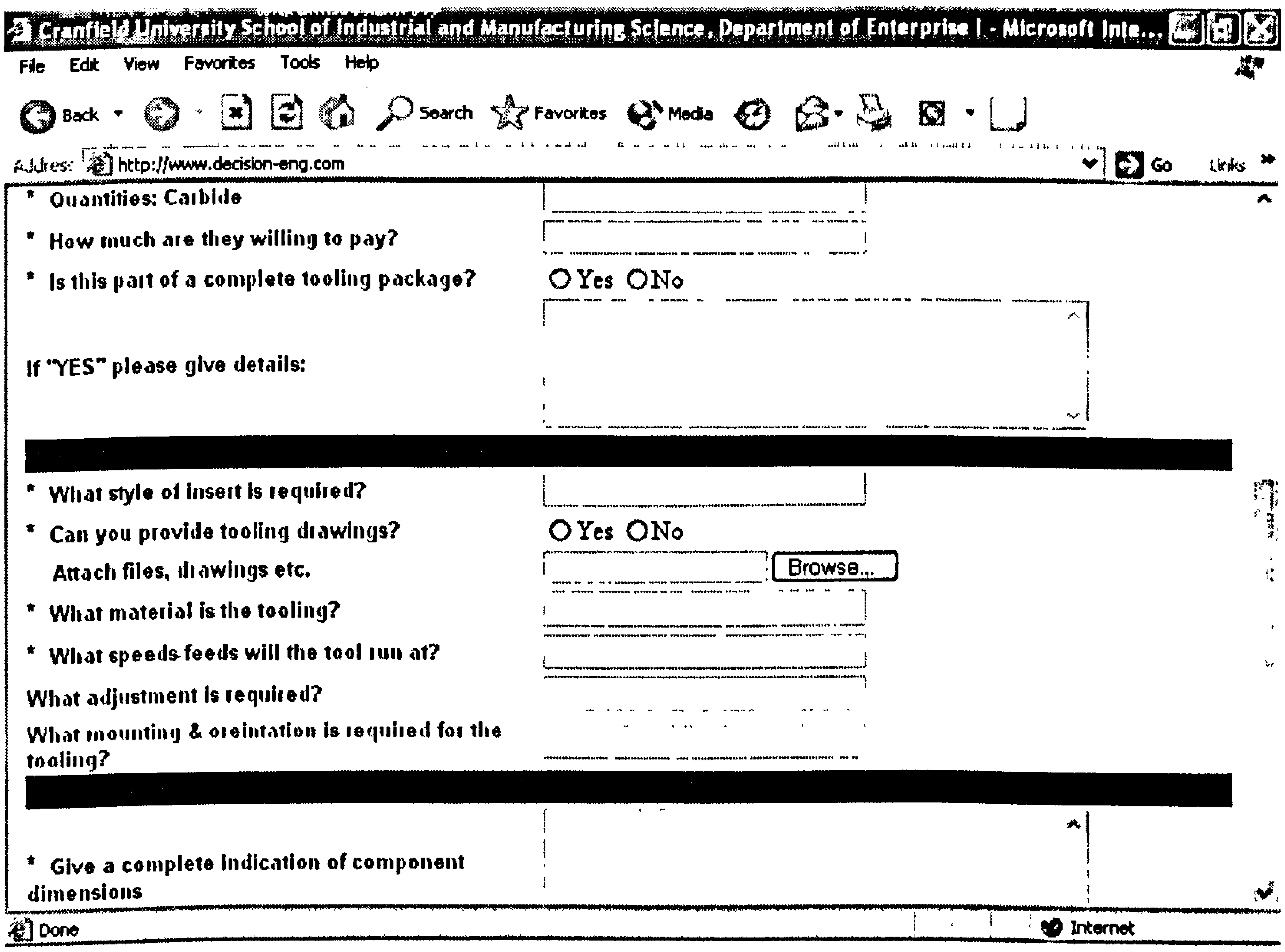


Figure B4: Example web-based proposal form for design type T6.

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APPENDIX C

Developing an ontology based framework for cutting tool design knowledge representation

C1 CUTTING TOOL DESIGN WORKSHOP

	Expert One	Novice	Expert Two
Function	Turning Undercutting Facing Produce surface finish Control Swarf	High speed machining High performance machine Reduce scrap Competitive advantage Cutting tool solution Cost reduction for production Offers a suitable cutting performance (M/c – product – condition) Achieve quality of production Achieve dimensions required Control heat propagation Control chip formation Shape formation Material Removal	Turning external Finish turning Control chip configuration Flexible insert selection Provide on m/c insert indexing Multi-directional cutting
Behaviour	Chip control Clearance angles Tool-life versus speed/feed Vibration free Achieve tolerances Power consumption	Chemical reaction Produce vibration Chip formation Less wear High temp resistance Material removal Surface finish Deformation of metal (shear)	M/c acute angles Good chip control at light D.O.C. Light cutting capability High speed m/c capability Provide good surface finish Provide good tool life at high speed
Structure	Secure top clamping with centre fixing Accurate insert & location Quick change shanks Tool protection (shim seat) Insert geometry for chip control Quality material for shank Chip gashes for chip removal	Material matrix Tool holders Coatings Cutting angles Clamp mechanisms Orientation Clearances Tool/product interface (shim) Tip radius Chip breakers	Modular – quick change tool concept Capable of auto loading from tool changer Indexable insert – grade + chip groove flexibility Negative rake + cost effective Pin lock + top clamp for good security (H + S)

C2 POINTS OF REFERENCE FOR INITIAL FBS

This section describes the locations of the terms found in figure 6.1, the initial function-behaviour-structure model. The terms were mainly found from the author's experience in the cutting tool design domain (informal discussions, chapter five of this research), industry literature, academic literature and the workshop mentioned above.

Term	Point of Reference
Function	
Remove Material	Obtained from the novice in the above-mentioned workshop. Also the industry related literature suggests that the ultimate goal for the metal cutting industry is to "remove metal". A corresponding behaviour described below will achieve this removal at a certain rate.
Define Form	Obtained as a term defined by the author during the development of an initial set of functions. The author considered the fact that the cutting tool would give a definition to the component and create the form as required.
Cost Effective	During informal discussion with members of the sponsoring organisation, the salespersons' need for a 'cost-effective' solution was raised.
Cutting Tool Solution	The novice in the workshop provided this as one of his opinions of a function that a cutting tool performs.
Quality	The cutting tool literature suggests that a cutting tool should produce a certain surface quality when machining a component. Also suggested by the novice in the above-mentioned workshop.
Time	The time taken to machine a component is an important consideration in the cutting tool industry. Within the industry reducing the time taken is a critical factor. Obtained from the cutting industry video and literature.
Behaviour	
Metal Removal Rate	Obtained from the industry literature and video during the development of cutting tool theory by the author, and also the workshop from both the experts and novice. This term will have consequences on the components selected for the cutting tool and hence a certain structure will be exhibited.
Chip Formation	Mentioned by all three participants in the workshop and through cutting tool literature and video lecture on cutting tools.
Heat Generation	From the literature and video on cutting tool industry, as the cutting tool interacts with the workpiece the phenomenon of friction occurs, this generates the heat.
Swarf Control	During the machining process chips are produced, effective chip or swarf control is required. This means that the swarf is removed from the cutting area. Found from the literature and videos.
Tool Wear	The action of two surfaces in contact will produce tool wear. Reduction of tool wear is important to the cutting tool industry considerable effort is given to solving this problem, the literature and video give plenty of advice on how to solve this problem.
Surface Finish	Considered by three participants of the workshop and designers during the design process. Literature gives a large amount of information on this phenomenon.
Produce Required Dimensions	From the analysis of the proposal stage of the design process as identified in chapter five.
Power Consumption	Cutting tool industry, literature & video and expert of the workshop. Obtained as a requirement in chapter five under the category of calculations.
Vibration	Obtained from expert one and the novice in the workshop. Vibration causes problems in many cutting operations e.g. surface finish, problems with machine etc. The cutting tool literature also identifies this as a problem.

Term	Point of Reference
Speeds & Feeds	The analysis in chapter five of the proposal stage as the designers considers these at the design stage. Obviously the literature and video provide information of these characteristics.
Cutting Temperature	Obtained from the literature and video lecture series. Cutting temperature is important for many reasons including the development of tool wear, surface finish amongst other considerations.
Cutting Time	From the analysis in chapter five. The manufacturing industry is trying to reduce this cutting time. Also the cutting tool designer must consider this during the insert/material selection.
Cutting Forces	From the analysis in chapter five. Considered by designers in the calculation stage of producing a design proposal.
Torque	Torque is considered an important factor by the literature and in the video lecture series. Also from the analysis in chapter five.
Cutting Velocity	Obtained from the literature and video series.
Comparison with competitor	From the analysis on chapter five and informal discussion with salespersons, a design consideration made by the designer and the salespersons when proposing a new cutting tool i.e. what has the competitor done better.
Competitive Advantage	From the analysis in chapter five. Is the cutting tool package provided going to give us a competitive advantage? Also a consideration from the business modules.
Cost	From the analysis in chapter five. A consideration that is required by both designers and salespersons regarding how the customer is willing to pay.
Technically viable	Informal discussion with cutting tool industry and video lecture series. A consideration that is made by the industry to identify whether the proposed cutting tool will satisfy the technical attributes of the proposal.
Technologically acceptable	Informal discussion with cutting tool industry and video lecture series. A consideration made by the industry to satisfy whether the cutting tool proposed is possible with the current technology available.
Economically viable	Informal discussion with cutting tool industry and video lecture series. A decision for the sponsoring company and competitors to ascertain whether it is economic for the sponsoring company to provide the proposed tooling and whether the customer will pay for the cutting tool proposed.
Increase revenue	Informal discussion with cutting tool industry and video lecture series. As with any industry increasing the revenue received from the sale of products is vital to their success.
Environmentally viable	Informal discussion with cutting tool industry and video lecture series. In the current industrial climate environmentally sound products that are considered throughout the lifecycle of the component i.e. design, manufacture, life and disposal phases.
Structure	
Type of Insert	Obtained from the table 5.5 in chapter five and also in the industry the literature. Also it is possible to identify the insert type on the designs themselves. It is a consideration that the designer takes into account, as the type of insert will exhibit a certain type of behaviour.
Cutting Envelope	A practical consideration obtained from interviews with designers in chapter five and experienced by the author in the descriptions of the designs carried out by the author in chapter four.

Term	Point of Reference
Depth of Cut	Obtained as part of the experience with cutting tool design, literature and videos and the analysis of proposal stage.
Type of Toolholder	Selection of the types of toolholder experienced by the author during designing of cutting tools with sponsoring organisation. Also suggested by the novice in the workshop.
Pocket	Experienced by the author during the design of cutting tools as a term for the area where an insert sits on the toolholder.
Length of Cutter	From the experience of the author within the cutting tool domain. It is designated on a design drawing. The length is an important dimension for the cutting tool.
Tolerances	Obtained from a variety of sources including author experience & participation within the sponsoring organisation and general design experience. Each mechanical component will have a tolerance limit designed into it. The workpiece will have tolerances to which the cutting tool must be designed to achieve.
Clearances	Obtained from a variety of sources including author experience & participation within the sponsoring organisation and general design experience. Also from the novice in the workshop.
Cutting Angles	Obtained from the literature and informal discussion with designer at sponsoring organisation. These can include angles on the insert itself and the angles, which the insert is placed on the toolholder.
Clamping Mechanisms	The component of the cutting tool system that holds the insert in place. The author experienced a wide variety of clamping mechanisms during design work carried out.
Chip Gash	The area behind the insert seat on the toolholder that gives the swarf an escape area otherwise the swarf would collect around the cutting area and cause problems. A term that was used in the industry and obtained during design work carried out by the author.
Orientation	A term used for the placement of the cutting tool e.g. whether left hand or right hand cutting. Also how the cutting tool is placed on the machine. A term used within the industry and obtained through informal discussion with the designers.
Type of Tool	A consideration from the experience of design work by the author as described in chapter four. What type of tool is suitable for this application? This recognition comes from experience of problem solving in the domain.
Workpiece	From the industry literature and experience in the domain. From this component within the cutting tool system the cutting tool can be designed.
Application/Process	Considering the application and process of the cutting tool occurs during the design process so this term has been obtained during the experience of the author during participation in the design process and in the analysis in chapter five.
Number of Inserts	Observations from design drawings. The number of inserts varies on the application of the cutting tool but this affects the cost of the tool.
Materials	Industry literature and experience of mechanical and manufacturing engineering.
Calculations	From the analysis of the proposal stage in chapter five. Occasionally the designer will have to some calculations in order to satisfy the technical requirements for the design.

Term	Point of Reference
Chip Breaker	A feature on the insert to break the chip formations as the cut is made. Industry experience has highlighted this term and suggested by the novice in the workshop.
Shim Seat	The interface between the insert and the toolholder. Highlighted during participation in the design process and the cutting tool industry literature.
Coatings	First mentioned during the author's experience in the domain, then further information obtained during video lecture on cutting tool industry and industry literature.

C3 CUTTING TOOL SYSTEM BASE-FUNCTION DESCRIPTIONS

This section presents the descriptions of the base-functions of the cutting tool system.

Function	System Component	Description
Holds Insert	Toolholder	The toolholder is the component of the cutting tool system that the insert is presented to the workpiece and as such the insert is held in place by an insert pocket and the clamping system. The 'holds insert' function can be achieved by considering the support has to be firm and by considering the standard features of the pocket area.
Transmits Force	Toolholder	The force for the insert to remove the material from the workpiece is provided by the machine, which the toolholder is attached too. Therefore the toolholder must transmit the force provided by the machine to the insert/workpiece interface. This 'transmit force' function can be achieved in several ways: by continuous contact, geometry of the pocket and how the toolholder is attached to the machine.
Protect Pocket	Clamping System	Part of the clamping system is the shim and the cartridge. A shim is slightly undersized and sits between the toolholder and the insert itself. A cartridge is an adjustable unit that houses the insert in an adjustable unit e.g. E-Z Set unit. One of the functions that either of these two systems can perform is protecting the pocket.
Locks Insert	Clamping System	Another function of the clamping system is to lock the insert into place and stop it from moving during the cutting process. This is achieved in a number of ways including screw & clamp.
Maximise Tool-life	Insert	During the cutting process a reduction in tool life will occur, the goal of the designer is to minimise this reduction or maximise tool-life. The ways which are linked to this sub-function are ways in which that this reduction can occur and therefore be able to consider factors that can decrease this reduction in tool-life.
Remove Material	Insert	The insert removes material from the workpiece

Function	System Component	Description
		by forming chips for a certain required surface finish to a desired shape and size. This function can be considered by anyone of these methods i.e. chip formation, required surface finish and desired shape & size.
Produce Shape	Insert	There different methods of producing a shape on a particular workpiece and these are the main types of machining e.g. turning, milling & drilling etc. This function can be considered using the factors that have to be considered when undertaking a design task that requires a turning process to be performed on the workpiece.
Attain Quality	Workpiece	The workpiece is having an operation performed on it by the cutting tool. The customer has specified that the component must have a certain quality when machining is completed. In this way the workpiece is attaining a certain level of quality during the machining process. This can be achieved by considering the surface finish required, the dimensional accuracy and the desired shape & size of the workpiece.
Gain Shape	Workpiece	During the cutting process the workpiece gains a shape even if the process for the cutting tool is machine the workpiece for a rough casting to a finished product. Considerations for this function are made on the application of the cutting tool, the cutting tool itself, the workpiece and the operation or process undertaken by the cutting tool.
Increase Value	Workpiece	A raw workpiece i.e. no work has been performed on it has a certain value associated with it. When a machining process is undertake on the workpiece it experiences an increase in value by virtue of having being worked on. It is now a more valuable workpiece. Two of ways of considering this function are by performance and cost of both the cutting tool and the workpiece.

C4 META-FUNCTIONS

This section presents the meta-functions that indicate how the base-functions relate to each other.

Number	Type	Description	Effects of meta-function
M1	Enhance	To enhance the production of shape	To provide support to insert To bring tool to the component
M2	Enhance	To enhance the removal of material	To lock insert into place Give rigid support To transmit force
M3	Provide	To provide the production of shape	To allow shape to be achieved Positions insert in the correct place
M4	Provide	To provide force to be transmitted	To produce chip formation To stop insert from moving
M5	Prevent	To prevent a decrease in tool life	To save costs To maintain quality of cut
M6	Enhance	To enable contact with component	Defined by insert Can hamper design of tool
M7	Control	To control the reduction in tool life	To maintain quality of cut To increase utility of tool
M8	Prevent	To prevent deterioration in shape	To save costs To produce surface finish To reduce scrap
M9	Control	To control the achieving of quality	To reduce tool wear To save costs
M10	Control	To control the achieving of quality	To get the correct depth of cut To select the optimal insert/material

Number	Type	Description	Effects of meta-function
			combination
M11	Drive	To enable the achievement of quality	To produce surface finish To produce Size & Shape
M12	Control	To control the gain in shape	To produce Size & Shape To control the depth of cut
M13	Provide	To provide an increase in value	To achieve dimensional accuracy To allow use of component
M14	Drive	To drive the gain in shape	To select the optimal insert/material combination To give shape & size to machine to
M15	Enhance	To enhance the increase in value	To achieve correct quality To increase cost of component
M16	Drive	To drive the increase in tool life	Which tool/material combination will be a success

C5 WAYS OF ACHIEVEMENT

This sections presents the 'ways of achieving'. A way describes how to achieve the base-functions given above. Basically the functions can be decomposed to reveal the information or knowledge required to solve it. A description is given of the way is given plus indication of the location of the way of achievement within the ontology-base framework.

Title	Description	Functional relation
Standard Features	The toolholder can be designed using the standard features that are always required on a toolholder no matter what the application or process that it undertakes.	Holds Insert
Continuous Contact	If the toolholder and the insert are in contacted at all times during the cutting application or process then this will be maintained.	Transmits Force
Geometry of Pocket	The geometry used for insert location allows the force to be transmitted.	Transmits Force
Machine Attachment	This is how the cutting tool is attached to the machine on which the cutting operation takes place. The machine attachment is often referred to as the 'back-end'.	Transmits Force
Shim	The shim is a plate 2-3mm thick that sits under the insert. It is usually very slightly undersized from the insert. They both sit the pocket.	Protect Pocket
Cartridge	An adjustable device that is replaceable in which the insert sits. The cartridge is then mounted onto the toolholder.	Protect Pocket Locks Insert
Cutting Pressure	When the insert is placed in position it is pull in tight to the toolholder by geometric design on the toolholder. During the cutting operation/process the pressure created by the contact of the insert and the workpiece locks the insert in place.	Locks Insert
Screw & Clamp	The main method for locking the insert in place.	Locks Insert
Surface Finish	The quality of the surface of the workpiece is one important criterion in cutting tool design. Different tool selections will be necessary for whether the job is for roughing, semi-finishing and finishing. The surface finish required on the workpiece will affect the tool-life.	Maximise Tool-life Attain Quality
Component Tolerances	The dimensional limits to which the cutting tool must provide so that the workpiece can be used for its intended application.	Maximise Tool-life
Cutting Force	The forces that are created during the cutting process affect the tool-life. The higher the forces the greater the wear on the cutting tool. Achieving the optimum angles for the cutting operations are essential here.	Maximise Tool-life
Dimensional Changes to Component	During cutting if there is a factor reducing the tool life then the problem can be identified by there being dimensional changes in the produced	Maximise Tool-life

Title	Description	Functional relation
	work pieces.	
Power Requirement	As the cutting tool insert begins to wear the sharpness of the cutting edge decreases. A greater friction is experienced and the power would need to be increased.	Maximise Tool-life
Chip Formation	The type of chip or swarf produced can help in determine the way the material is removed and help in increasing the cutting tool life.	Maximise Tool-life Remove Material
Required Finish	The required finish on the workpiece determines the manner in which the metal is removed.	Remove Material
Desired Shape or Size	The workpiece dimensions helps to determine the manner in which the material is to be removed.	Remove Material
Boring	Boring, also called Internal Turning, is used to increase the inside diameter of a hole.	Produce Shape
Turning	Used for the generation of cylindrical surfaces with a single point tool. Either the workpiece or the tool rotates.	Produce Shape
Drilling	The main method used in the manufacturing sector for producing holes.	Produce Shape
Trepanning	In trepanning the cutting tool produces a hole by removing a disk shaped piece also called slug or core, usually from flat plates. A hole is produced without reducing all the material removed to chips, as is the case in drilling.	Produce Shape
Grooving	Grooving is a single point machining operation performed on lathes, automatic lathes, or machining centers. The purpose here to produce a groove or thread in the surface both externally and internally.	Produce Shape
Milling	The process of generating machined surfaces by progressively removing a predetermined amount of material or stock from the workpiece, which is advanced at a relatively slow rate of movement or feed to a milling cutter rotating at a comparatively high speed. The characteristic feature of the milling process is that each milling cutter tooth removes its share of the stock in the form of small individual chips.	Produce Shape
Application	This is given to highlight whether the designed cutting tool is one of the major applications of metal cutting. Each individual application produces the shape on a component in a different manner.	Gain Shape
Tool	Details about the cutting tool. The type of insert used, the cost of the cutting tool and speeds and feed that the cutting tool will operate at.	Gain Shape
Workpiece	Details about the workpiece itself such as the material, surface finish requirements and costs are examples.	Gain Shape
Operation/Process	The way that the cutting tool works in its operating environment. For instance the way it moves relative to the workpiece, its mounting to	Gain Shape

Title	Description	Functional relation
	the machine etc.	
Dimensional Accuracy	To attain quality in the workpiece the designer would consider that three elements are catered for in the design and a balance is achieved in these. Dimensional accuracy refers to the cutting tool actually doing as requested so that the workpiece will do the job specified.	Attain Quality
Shape & Size	Selecting a cutting tool that would be technically appropriate for the workpiece is the goal here by considering the size and shape of the component. The case being illustrated in the examples given in this research in chapter four. Different size and shape of component will give rise to a different cutting tool.	Attain Quality
Performance	Both the cutting tool and the workpiece selection affect performance of the system. This is about obtaining the appropriate specifications of the cutting tool, which would perform as required by the designer and the customer.	Increase Value
Cost	This can be considered for both the cutting tool and the workpiece. Depending on what is required there are a number of choices available to the designer as to how to achieve the most beneficial balance of cost to both the customer and sponsoring organisation.	Increase Value
Quality	The level of surface finish, dimensional accuracy and workpiece shape & size will affect the increase in value of the workpiece. What has to be done to the component to achieve the requirements set by the customer?	Increase Value
Time	The time taken to produce the workpiece will have a bearing on the level to which the value of the workpiece increases. How long will the design lead-time be? How long will it take to produce the desired shape?	Increase Value
Commercial	The information about the customer and competitor that is required by the designer to produce a competitive product for the market place.	Increase Value

C6 WAY OF ACHIEVEMENT DIAGRAMS

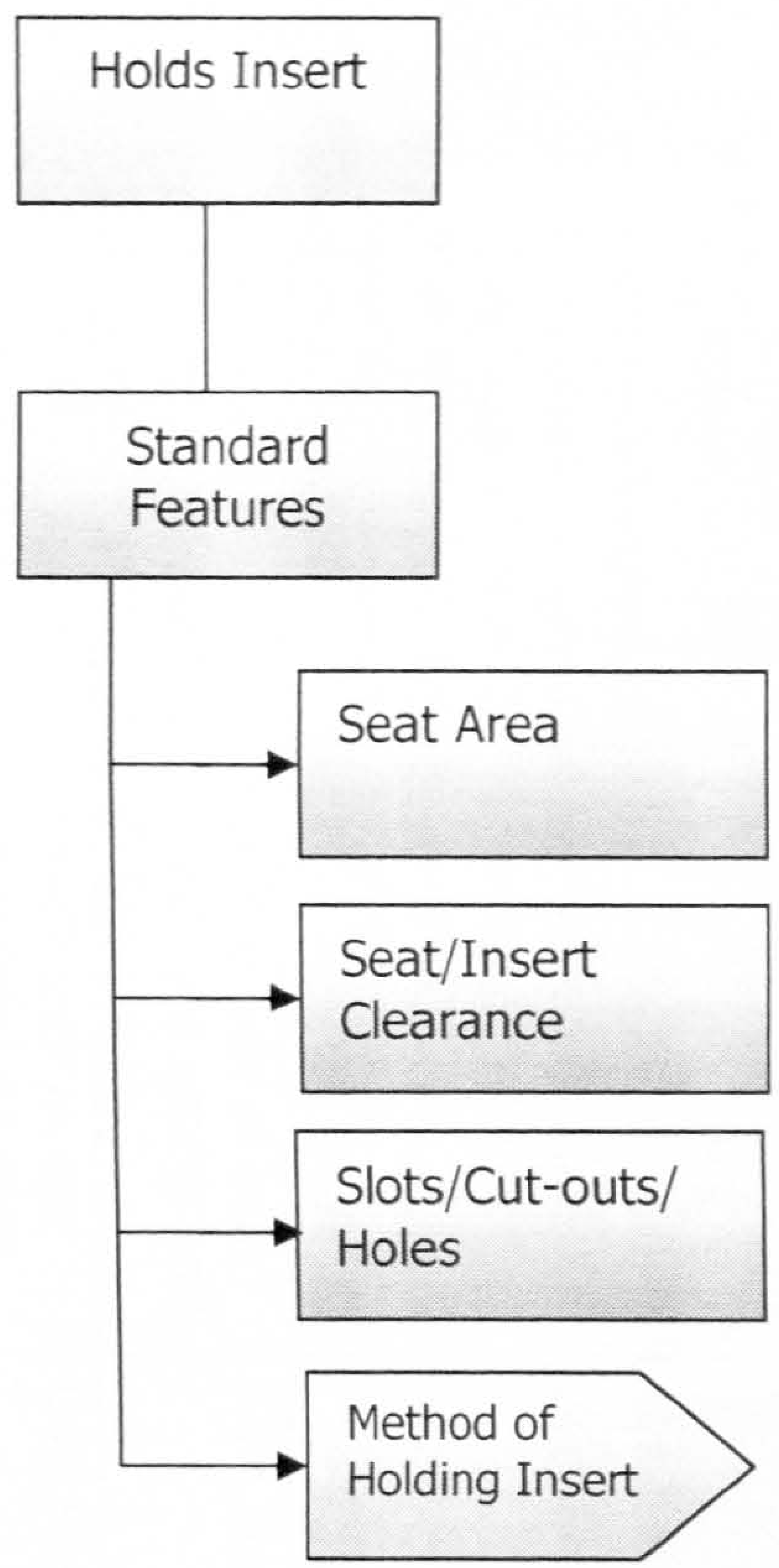


Figure C1: Design considerations for the function 'Holds Insert'.

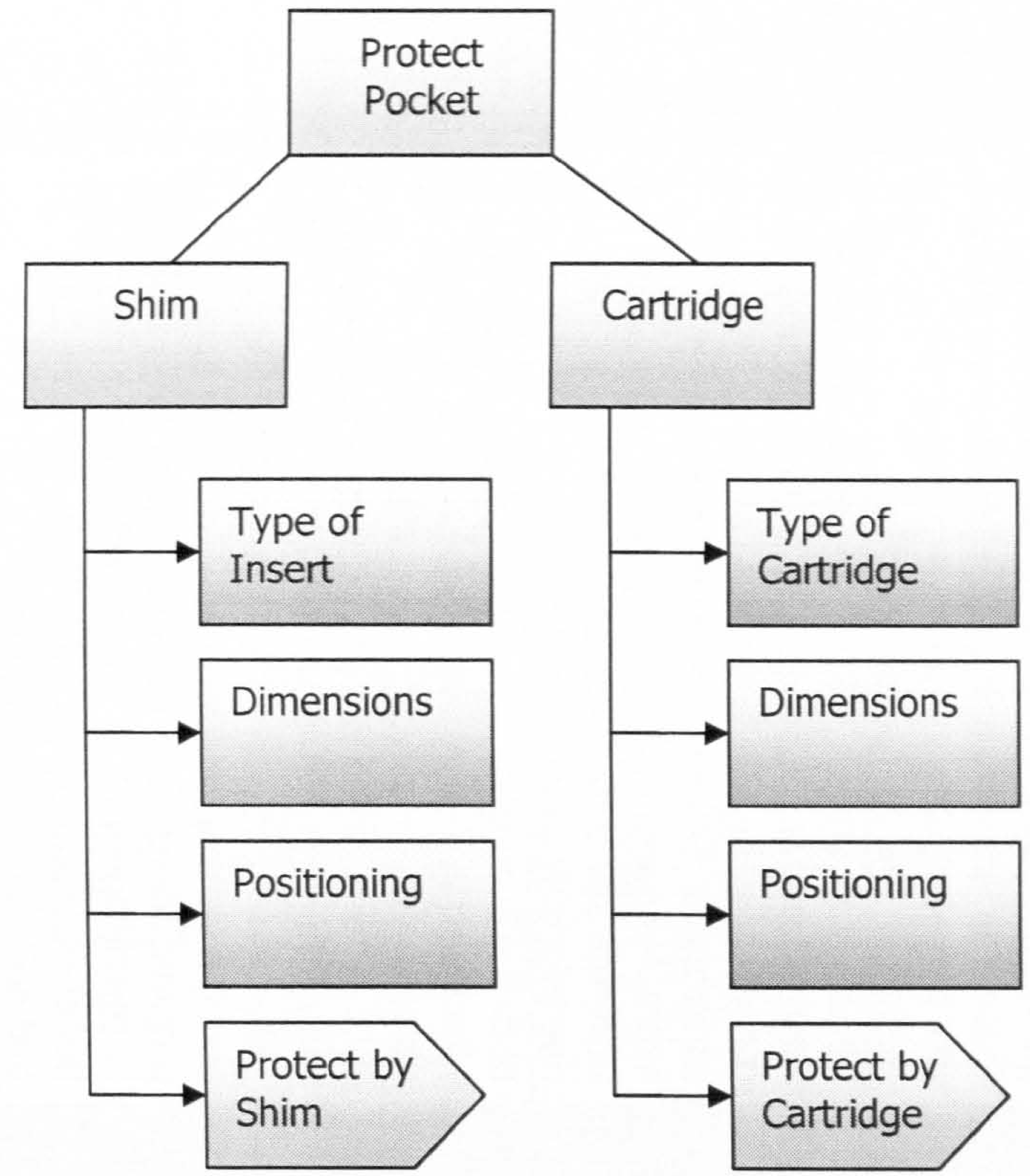


Figure C2: Design considerations for the function 'Protect Pocket'.

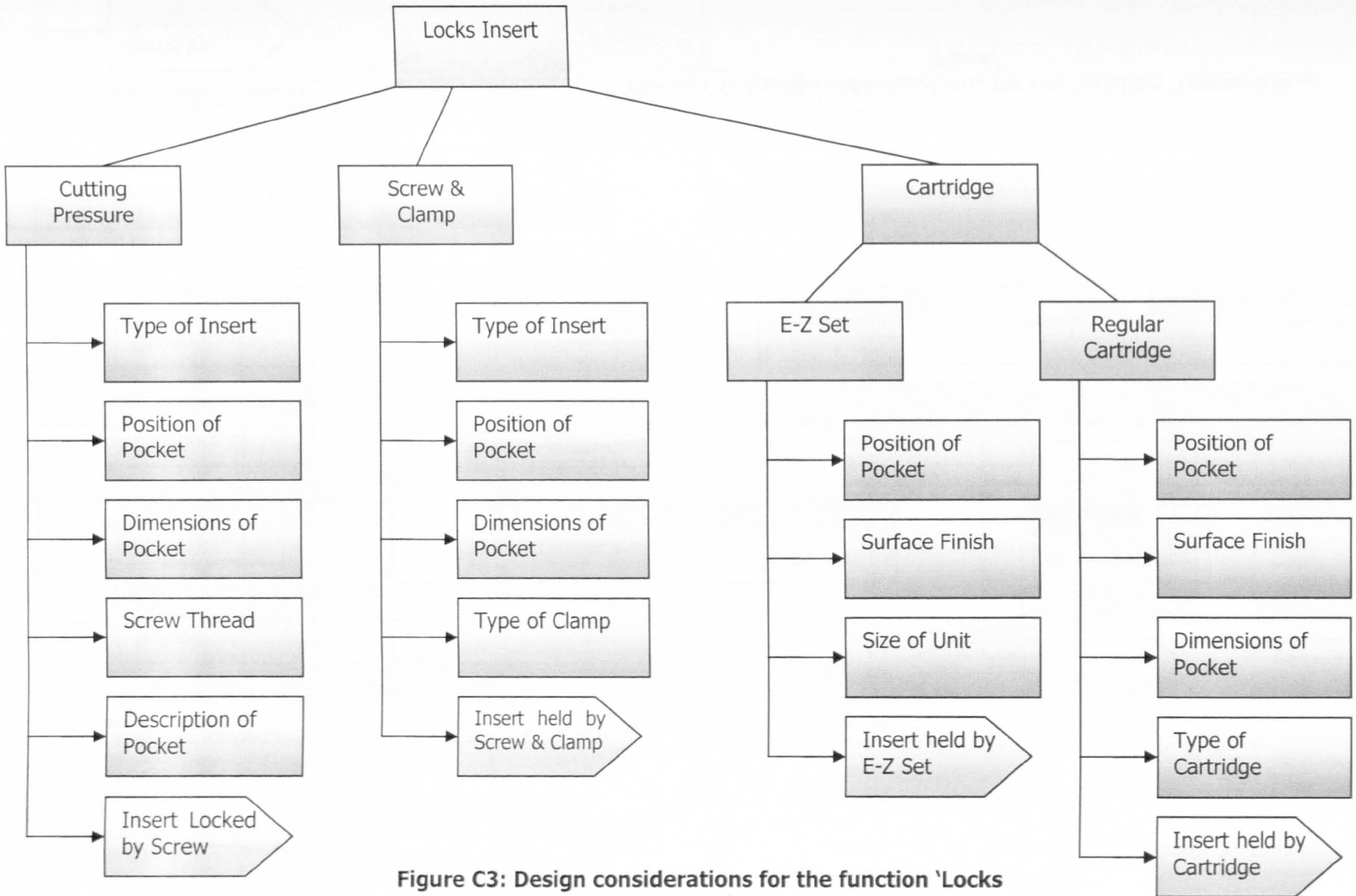


Figure C3: Design considerations for the function 'Locks Insert'.

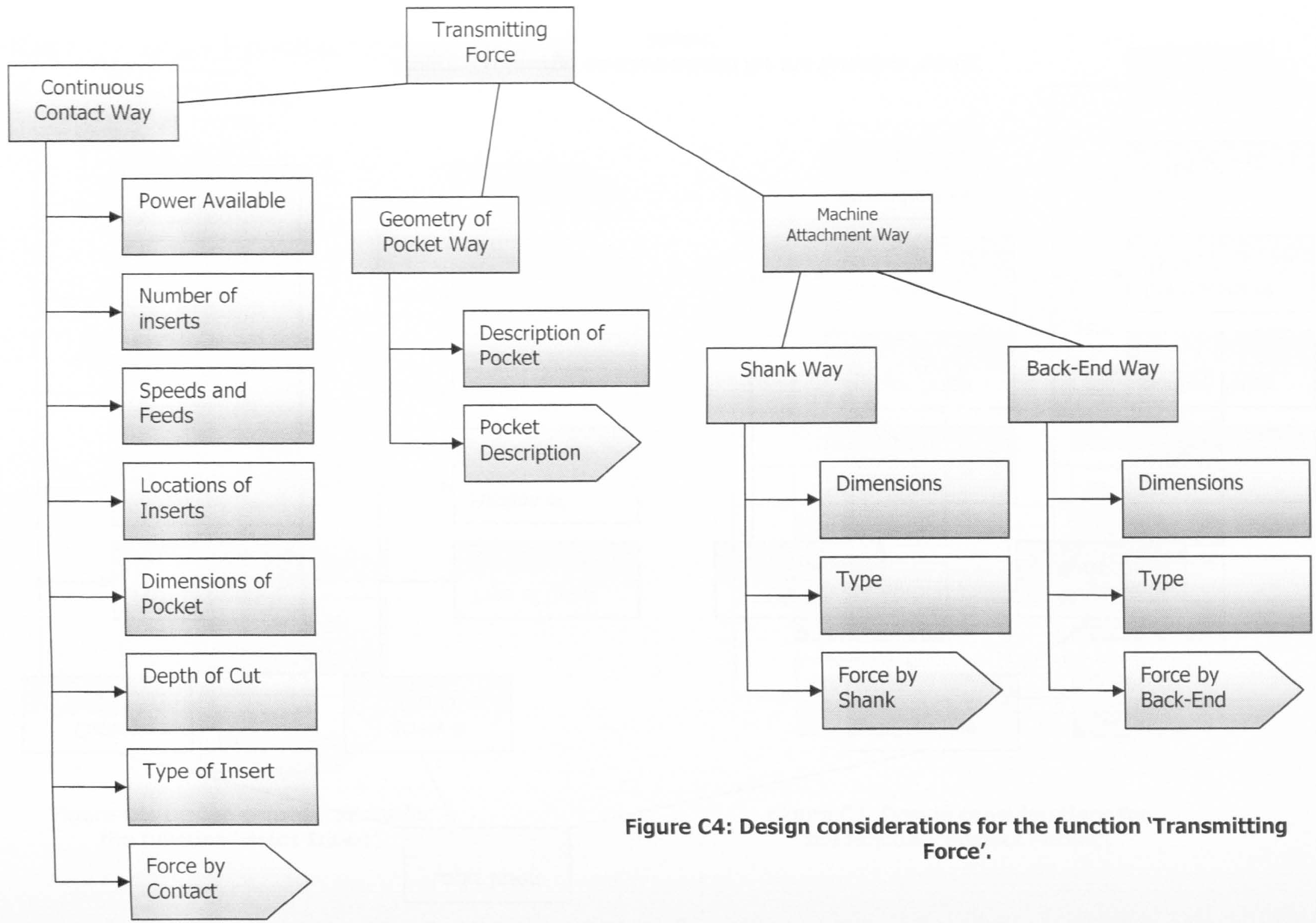


Figure C4: Design considerations for the function 'Transmitting Force'.

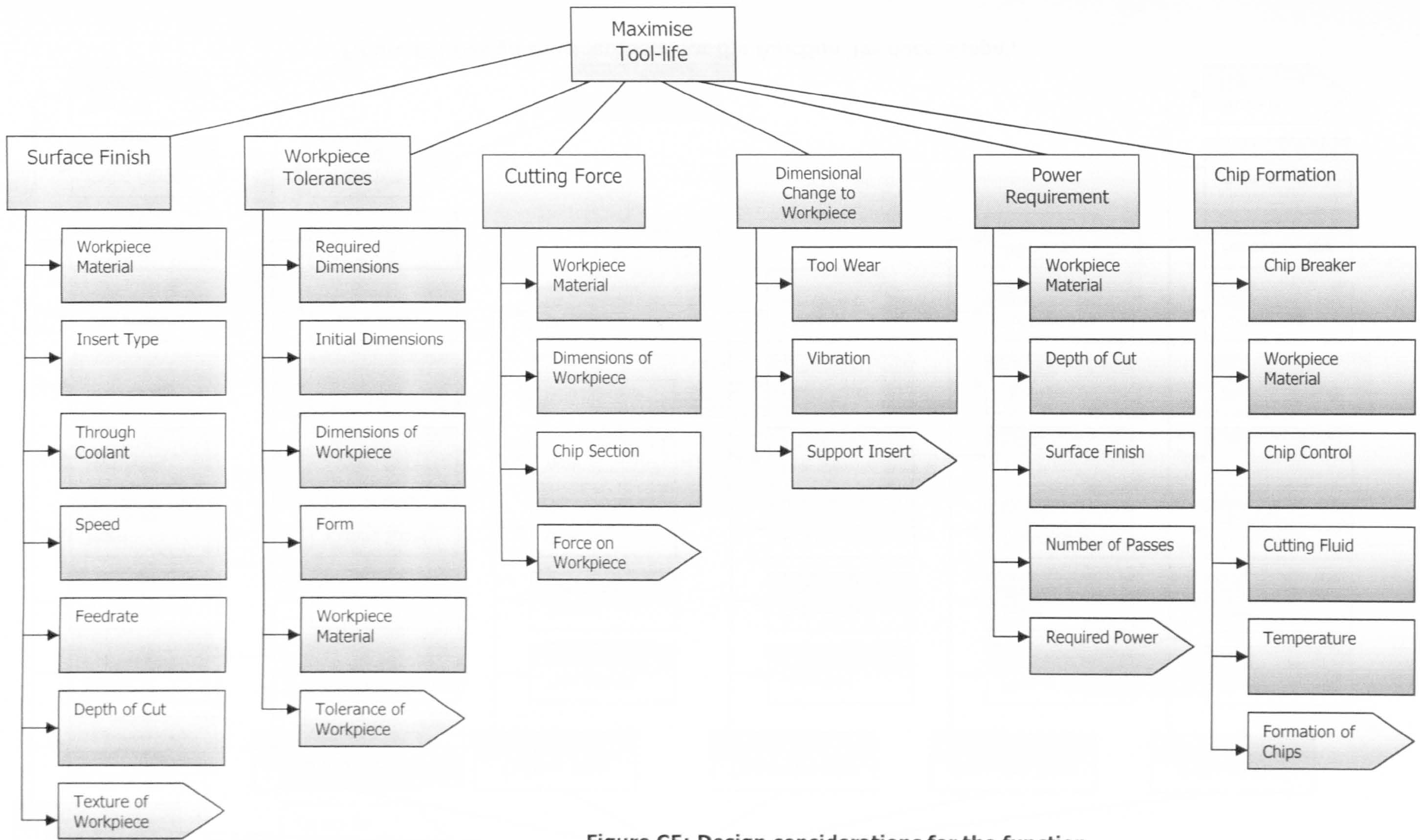


Figure C5: Design considerations for the function 'Reduction in Tool Life'.

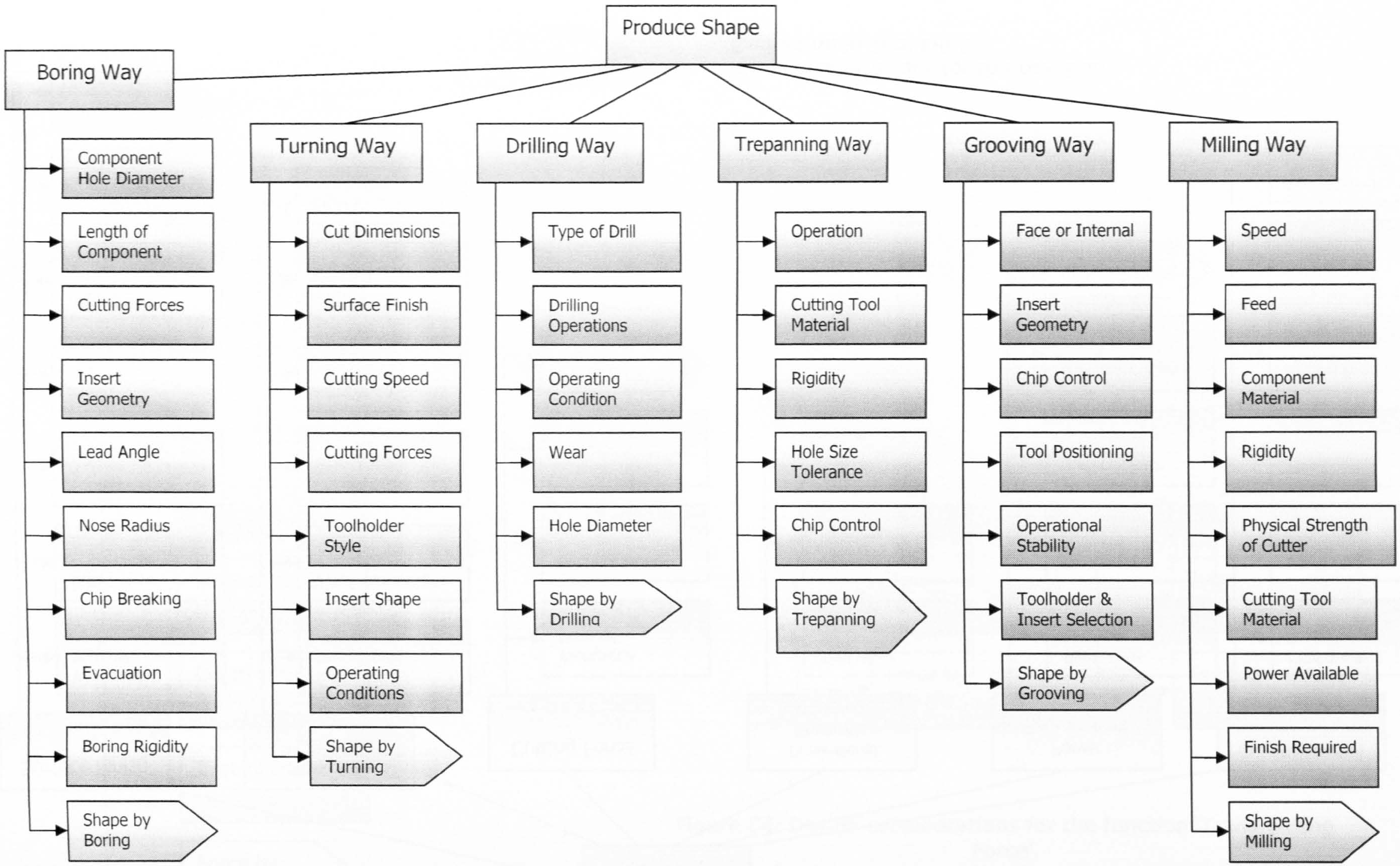


Figure C6: Design considerations for the function 'Produce Shape'.

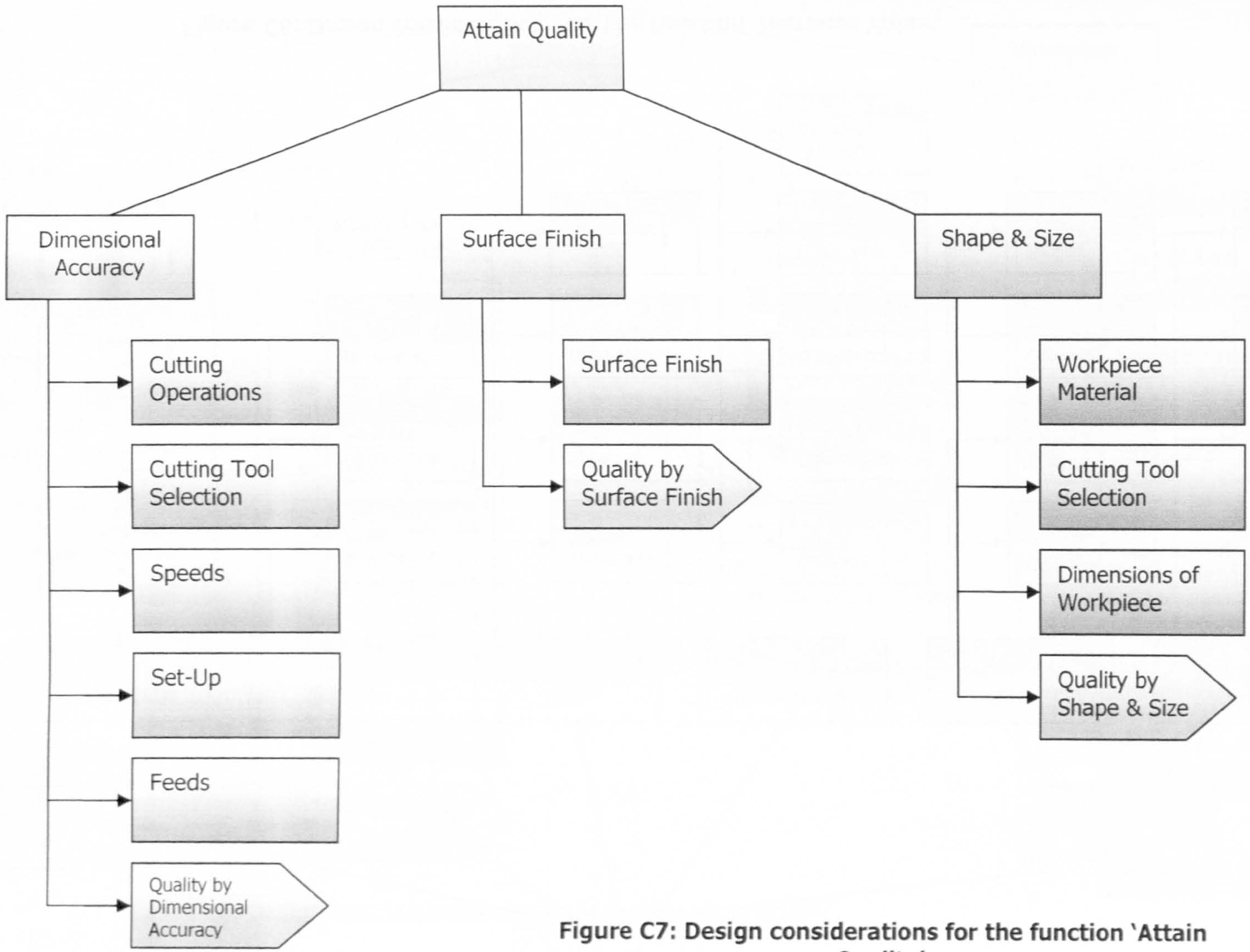


Figure C7: Design considerations for the function 'Attain Quality'.

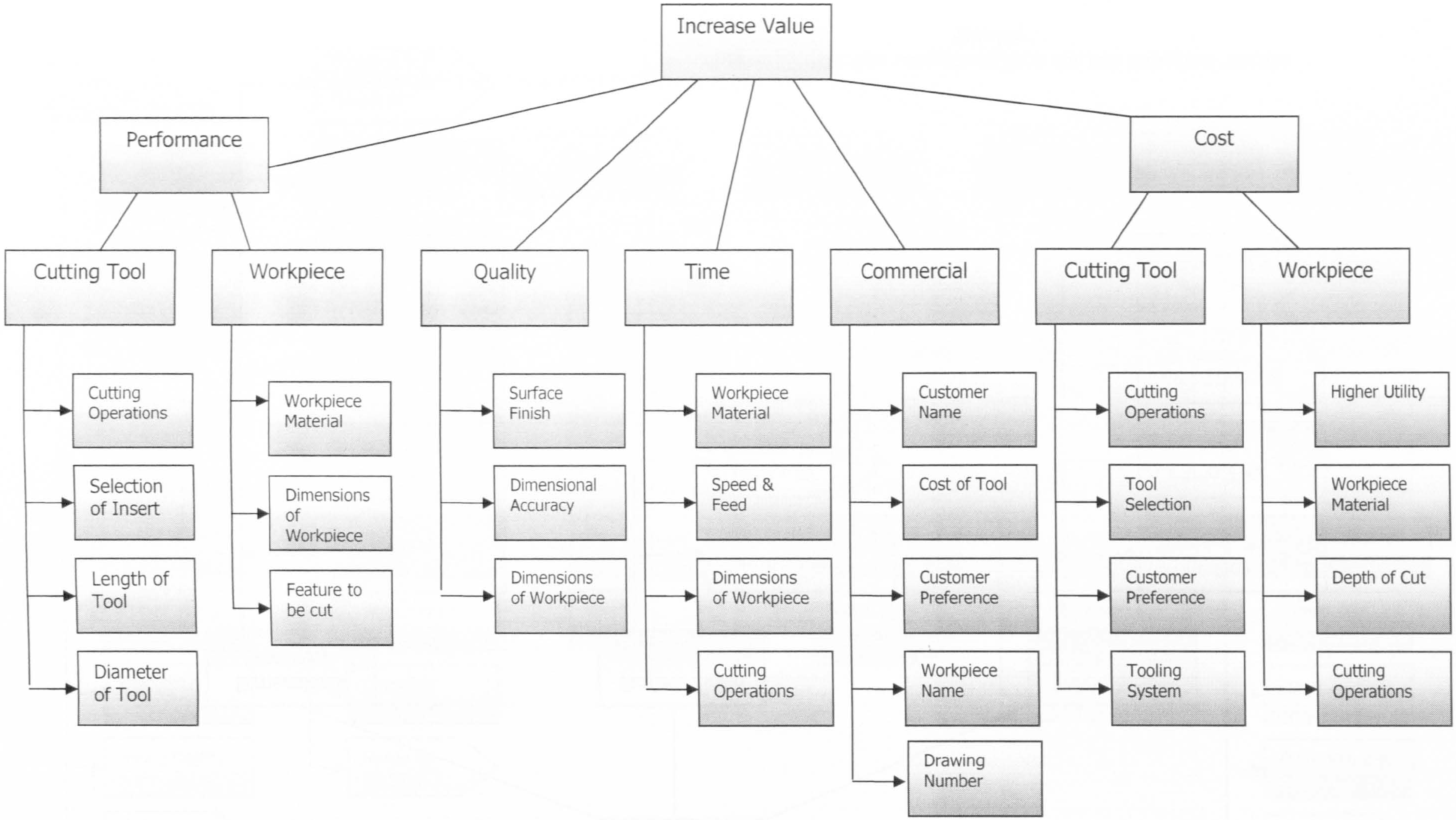


Figure C8: Design considerations for the function 'Increase Value'.

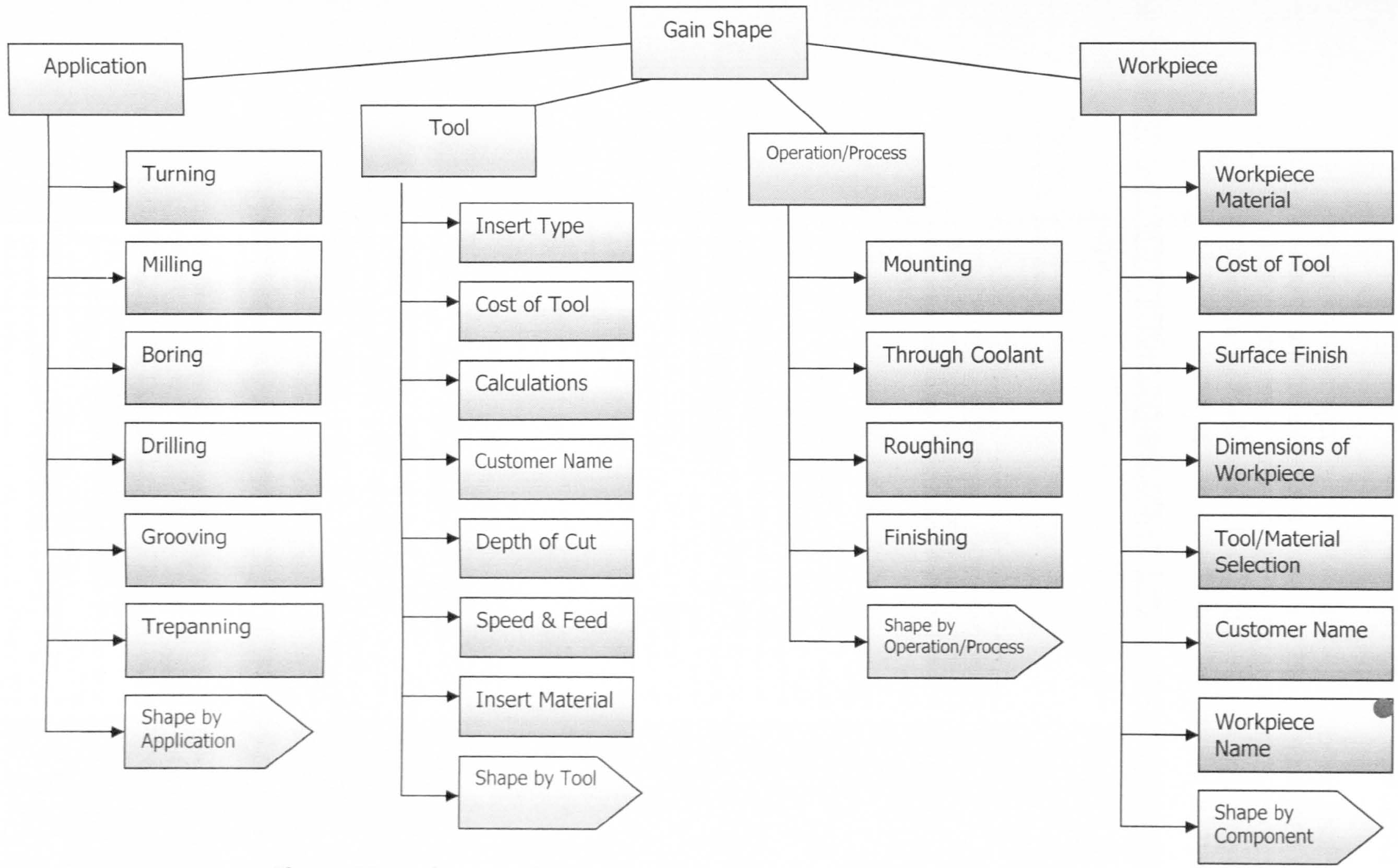


Figure C9: Design considerations for the function 'Gain Shape'.

C7 DESIGN CONSIDERATIONS

The design considerations show how the ways of achievement are solved using domain knowledge. These are interpretations of the criteria from the questions of the third column in table 5.5 of chapter 5 and the initial function-behaviour-structure model shown figure 6.1. The domain schema refers to the sub-function that the design consideration is a part of.

Title	Description	Functional relation
Cutting Operations	The operations that have to be performed on the workpiece in order to produce the form required.	Cost: Component Cost: Cutting Tool Time Performance: Cutting Tool Dimensional Accuracy Drilling
Higher Utility	The increase in profitability of the workpiece after the machining has been carried out.	Cost: Component
Cutting Tool Selection	A guide to what range of choices available to the designer and an indication as to why the chosen design was selected.	Cost: Cutting Tool Dimensional Accuracy Shape & Size
Drawing Number	A designation that identifies the design drawing/s within the organisation.	Commercial
Customer Preference	In many cases the customer will give a preference to which tooling they require.	Commercial Cost: Cutting Tool
Cost of Tool	The value given in a quotation to the customer. Based on the decisions made for the type of tool required for the application.	Commercial Tool Component
Customer Name	Important to identify who is requiring the tool. Designers can identify if they have done work for this organisation previously.	Commercial Component Tool
Dimensions of Workpiece	The larger the component the more time it will take to machine the component.	Time Performance: Component Shape & Size Component Quality Desired Shape or Size Cutting Force Workpiece Tolerances
Dimensional Accuracy	The level of dimensional accuracy required for the cutting tool to achieve.	Quality
Feature to be Cut	The area/s on the workpiece that require/s the machining process.	Performance: Component
Diameter of Tool	Gives an indication of the physical size of the cutting tool. A way of selecting past designs by comparing the diameter.	Performance: Cutting Tool
Length of Tool	Gives an indication of the physical size of the cutting tool. A way of selecting past designs by comparing the length.	Performance: Cutting Tool
Selection of Insert	With a variety of inserts to choose from it is useful to have the selected insert for the application and why it was selected.	Performance: Cutting Tool
Set Up	The information regarding how the tool will be used in the application and how it is set-up in the machine.	Dimensional Accuracy
Mounting	Attaching the cutting tool to the machine it will run on requires knowing about the mounting or 'back-end' style to be designed onto the toolholder.	Operation/Process
Component Name	For the identification of the designs and proposals by comparing components that have similar solutions.	Component

Title	Description	Functional relation
Tool/Material Selection	The comparison of the insert selected for the workpiece material to be cut.	Component Trepanning
Insert Material	The base material of the insert. Most often inserts are made of carbide then coated for wear properties.	Tool Milling
Trepanning	A description of the design of the trepanning tool.	Application
Grooving	A description of the design of the grooving tool.	Application
Drilling	A description of the design of the drilling tool.	Application
Boring	A description of the design of the boring tool.	Application
Milling	A description of the design of the milling tool.	Application
Turning	A description of the design of the turning tool.	Application
Power Available	The capability of the machine that the tool is being designed for.	Milling Continuous Contact
Physical Strength of Cutter	Consideration as to whether the designed cutting tool will be strong enough to do the job at hand.	Milling
Operational Stability	When the cutting tool is operating vibration or other forces that cause it to be unstable do not affect it.	Grooving
Face, Internal or External	Description of which type of tool has been designed.	Grooving
Hole Size Tolerance	The dimensional limits of the hole to be machined.	Trepanning
Hole Diameter	The dimensions of the hole to be drilled.	Drilling
Type of Drill	A technical description of the drill that is being designed.	Drilling
Operating Conditions	A description of the environment that the cutting tool is to operate in.	Turning Drilling Trepanning
Evacuation	The removal of the cut material has to be considered.	Boring
Thickness of Workpiece	The depth that the cutting tool will have to bore the hole too.	Boring
Workpiece Hole Diameter	The diameter of the hole that is required by machining of the workpiece	Boring
Indexable Cutting tool	There are four basic shapes and several special shapes available to the cutting tool designer, each having its own strengths and weaknesses giving different cutting characteristics and economics. Being indexable means that the insert does not have to be reground when worn but merely turned to a fresh cutting edge and used again.	Chip Formation
Geometry of Cutting Tool	The geometry of the insert is of primary concern here. Different cuts can be obtained by choosing different geometries of insert. Also the angles that are formed when the insert is placed on the toolholder will have to be considered to produce the required cut.	Chip Formation
Temperature	Too much in the cutting zone leads to rapid tool wear and hence a reduction in tool life.	Chip Formation
Cutting Fluid	To reduce the temperature and help the cutting of the material a coolant is used.	Chip Formation
Chip Breaker	A feature on the insert that aids in the breaking of the chip during the cutting process. Generally these are all ready on the chosen insert but it depends on the type of material that is to be cut. If it is a brittle material that chips easily then a chip breaker might not be necessary. However, if a ductile material is machined then the chips can be continuous which require the chip breaker.	Chip Formation Boring Trepanning Grooving
Number of Passes	The number of time the cutting tool must pass over the workpiece to remove the material to the required dimensions.	Power Requirement
Vibration	Any out of balance forces experienced during the	Dimensional Change to Component

Title	Description	Functional relation
	rotation of the cutting tool. Can lead to inaccuracies in the dimensions of the workpiece or breakages.	
Tool Wear	Cutting tool life is probably one of the most important economic considerations in the tooling industry. As the material removal takes place, the insert will wear, that is, there will be some degradation of the surface of the insert, which will eventually lead to dimensional inaccuracies in the work-piece. Adequate consideration must be made to the tool wear by considering the material/geometry combinations of the cutting tool.	Dimensional Change to Workpiece Chip Formation Drilling
Chip Section	The thickness of the chip upon the cutting edge making contact with the workpiece.	Cutting Force
Initial Dimensions	The dimensions of the workpiece before any work is carried out on it.	Workpiece Tolerances
Required Dimensions	The dimensions that are required by the component drawings.	Component Tolerances
Through Coolant	The coolant holes are part of the cutting tool e.g. bored into the toolholder body.	Surface Finish Operation/Process
Workpiece Material	This material will affect the selection of the insert, speeds, feeds, and geometries that are used to remove the material from the workpiece.	Surface Finish Component Tolerances Cutting Force Power Requirement Chip Formation Desired Shape or Size Milling Component Shape & Size Performance: Component Time Cost: Component
Size of Unit	The physical dimensions of the cartridge or E-Z Set unit to be used usually given in an industry standard format.	Cartridge: E-Z Set
Surface Finish	The selection of the level of surface finish required by the customer for the workpiece. A choice is made as to whether it is to be roughing, semi-finishing or finishing. In a multi-tool job the tools may do a couple of the surface finishes mentioned.	Required Finish Operation/Process Surface Finish Cartridge: E-Z Set, Regular Cartridge Power Requirement Turning Milling Component Quality
Description, Dimensions of Pocket	The dimensions for producing the pocket for the insert on the toolholder are given by a standard drawing that gives the detailed manufacturing instructions for the producing of the insert pocket on the toolholder. This would be for any given insert by the cavity sheet available from insert libraries. Record the cavity sheet drawing number.	Cutting Pressure Geometry of Pocket Cutting Pressure Screw & Clamp Continuous Contact Cartridge: Regular Cartridge
Screw Thread	The dimensions of the screw thread used in holding the insert. Given using an industry recognised format. Record the type of screw thread used.	Cutting Pressure
Position of Pocket	Generally given by the details on the cavity sheet. For special designs record as per given on cavity sheet.	Cutting Pressure Screw & Clamp Cartridge: E-Z Set, Regular
Positioning	The position of cartridge and Shim are given in the catalogues for the individual components.	Shim Cartridge
Type of Cartridge	Record the information given for the cartridge as is given in the catalogues	Cartridge: Regular Cartridge
Type of Insert	Round, Square, Triangular, Parallelogram plus others. From the many inserts to choose from, record the type of insert chosen written in the	Shim Cutting Pressure Screw & Clamp

Title	Description	Functional relation
	industry standard method.	Surface Finish Tool Turning Continuous Contact
Calculations	On occasion there is the need for calculations for calculating forces, bending, power requirements etc. A record of the calculations is suggested here.	Tool
Size of Insert	The Inscribed Circle (I.C.) diameter of the insert should be given. All inserts in the cutting tool industry have a I.C.	Continuous Contact
Type	Usually given by the customer for their type of machine but otherwise refer to previous work carried out for the customer.	Machine Attachment: Shank, Back End
Dimensions	Dimensions for the shanks and back-ends are in form used as standard for the industry derived from international standards.	Machine Attachment: Shank, Back End Shim Cartridge
Depth of Cut	The amount of material to be removed given in mm. Can be removed by a number of passes.	Continuous Contact Surface Finish Power Requirement Chip Formation Tool Cost: Component
Locations of Inserts	A description of where the inserts have been placed. Radii from the centre line of the cutting tool and the angles in 360 degrees that the inserts are placed.	Continuous Contact
Speeds & Feeds	The approaching rates and removal rates for the cutting tool relative to the workpiece.	Continuous Contact Surface Finish Turning Milling Tool Dimensional Accuracy Time
Number of Inserts	The total number of inserts that the cutting tool incorporates.	Continuous Contact
Slots/Cut-outs/Holes	Additional features of the cutting tool that needs mentioning.	Standard Features
Seat Area	The area of design on the toolholder for the insert placement	Standard Features
Forces	The forces required in removing the material from the work-piece. Especially important if the cutting tool is of length that might induce bending when cutting. In milling applications this can be necessary if the power of the machine is in doubt.	Chip Formation
Plastic Deformation	Due to the high pressure at the point of contact between the insert and the work-piece the material will deform. This will have an affect on the chip formed and subsequently the effect the removal of the material.	Chip Formation

C8 CASE STUDIES

Case Study Two: E-Z Set Cutter

Table C1: Ontology framework for case two: E-Z Set cutter.

Ontology Element	Description of Value	Explanation
Component	Workpiece	The concentration of the design effort is around the E-Z Set unit, which contains the insert and the micro-adjustable unit, therefore the selection of the insert component to base the design knowledge on.
Function	Increase Value	By performing a machining task on the workpiece value is being added to the component.
Way of achievement	Performance	The design considerations for performance include both the considerations for the tool as well as the workpiece in order to increase the value of the workpiece.
Design Considerations		
Cutting Operations	Centre line and move to surface	The cutting tool will approach on the centre line of the bore and then move to the surface before removing the material.
Selection of Insert	Chosen with the E-Z Set Unit	The E-Z Set unit designate the selection of an insert, as a certain type of insert will fit a size of unit. Choosing an E-Z set unit the nose radius of the insert will be defined and then a triangular insert will be used.
Length of Tool	236mm over 0.40 M.I.R. 221.48mm±0.03 to tooling hole	Two lengths are given here both from the back-face of the shank shoulder. The first shows the total length over the insert (236mm), and the second is the distance to the tooling hole (221.48mm). This important as it gives the machinist of the toolholder a point to machine the pocket of the E-Z Set unit to be machined.
Diameter of Tool	36.576mm over 0.40 M.I.R.	This is the diameter at the cutting end of the cutting tool. Again this is given as an over insert dimension
Workpiece Material	Aluminium	Most cylinder heads manufactured by the automotive industry are made of aluminium. This required this level of design consideration as the material of the component will limit the selection of insert and E-Z Set unit. Aluminium is a soft well machinable material.
Dimensions of Workpiece	60mm Bore diameter	The diameter of the bore in this is 60mm enough space for the cutting tool perform the operation on the workpiece. Needed so that the designer can decide what size of

		unit to select from the catalogue.
Feature to be cut	Cylinder Bore	This component is a cylinder head and the cutting tool is required to finish machine cylinder. That is, it is to produce a quality finish to the internal surface, which is contact with the cylinder during the work piece's operation.
Ontology Element	**Description of Value**	**Explanation**
Component	Workpiece	In this design consideration is given to the workpiece due to the narrow access area, thus the selection of a function from those on the workpiece.
Function	Gain Shape	The workpiece is being bored out so that workpiece is beginning given its final shape.
Way of achievement	Tool	The tool doing the machining has a calculation required for it to be designed therefore in this case select the design consideration on the cutting tool.
Design Considerations		
Insert Type	CPGW 050204	The insert is diamond shaped (C) with an 11° clearance (P) with a 5mm (05) Inscribed Circle (I. C.), a 2mm thickness (02) and a tip radius of 0.4mm (04).
Cost of Tool	£200	Only relevant if the customer asks for a particular cost target but as none was given here then it is placed here for the sponsoring companies interest. For design reuse i.e. searching for designs it is probably not useful because this is a special and there would not be another like it.
Calculations	For the calculation of the tooling hole	A calculation is required (see chapter four, section 4.4.3, table 4.4) which calculates the distance of the tooling hole from the back shoulder of the shank. This tooling hole allows the machinist to pivot the toolholder here and rotate by 53° 8′ and machine the pocket.
Customer Name	Given	The customer name is given but for confidentiality reasons it is not possible to show in this research. The customer name is important to identify firstly who is the design work for and then to begin to design for that customer.
Depth of Cut	0.30 mm	Because only a finish cut is required only a small quantity of material is being removed.
Speed & Feed	Not given	Within the limits of a standard operation of the E-Z Set unit chosen, therefore no need to consider it.
Insert Material	Carbide	The inserts used are made of coated carbide. Most inserts used today in the cutting tool industry are of a coated carbide variety.
Ontology Element	**Description of Value**	**Explanation**
Component	Clamping Mechanism	The focus of the design work is on the E-Z Set unit, which affectively clamps the

		insert into place.
Function	Locks Insert	It is a type of cartridge unit that locks the insert into place. However, there is a small micro-adjustment to gain extra cutting diameter.
Way of achievement	Cartridge: E-Z Set	The unit that locks the insert into place. A set of calculations is required upon the selection of the size of unit to be used based on the minimum diameter that can be allowed.
Design Considerations		
Position of Pocket	221.48mm±0.03 to tooling hole. Rotate 53° 8′ anti-clockwise	A calculation is required (see chapter four, section 4.4.3, table 4.4) which calculates the distance of the tooling hole from the back shoulder of the shank. This tooling hole allows the machinist to pivot the toolholder here and rotate by 53° 8′ and machine the pocket.
Surface Finish	Finish	The customer requires a finished surface.
Size of Unit	'A' (minimum bore diameter = 25.4mm	The unit size is designated 'A' in the catalogue and it has minimum bore diameter of 25.4mm. That is, the minimum diameter of the toolholder = 25.4mm to allow enough material.

Case Study Three: Special Grooving Cutter

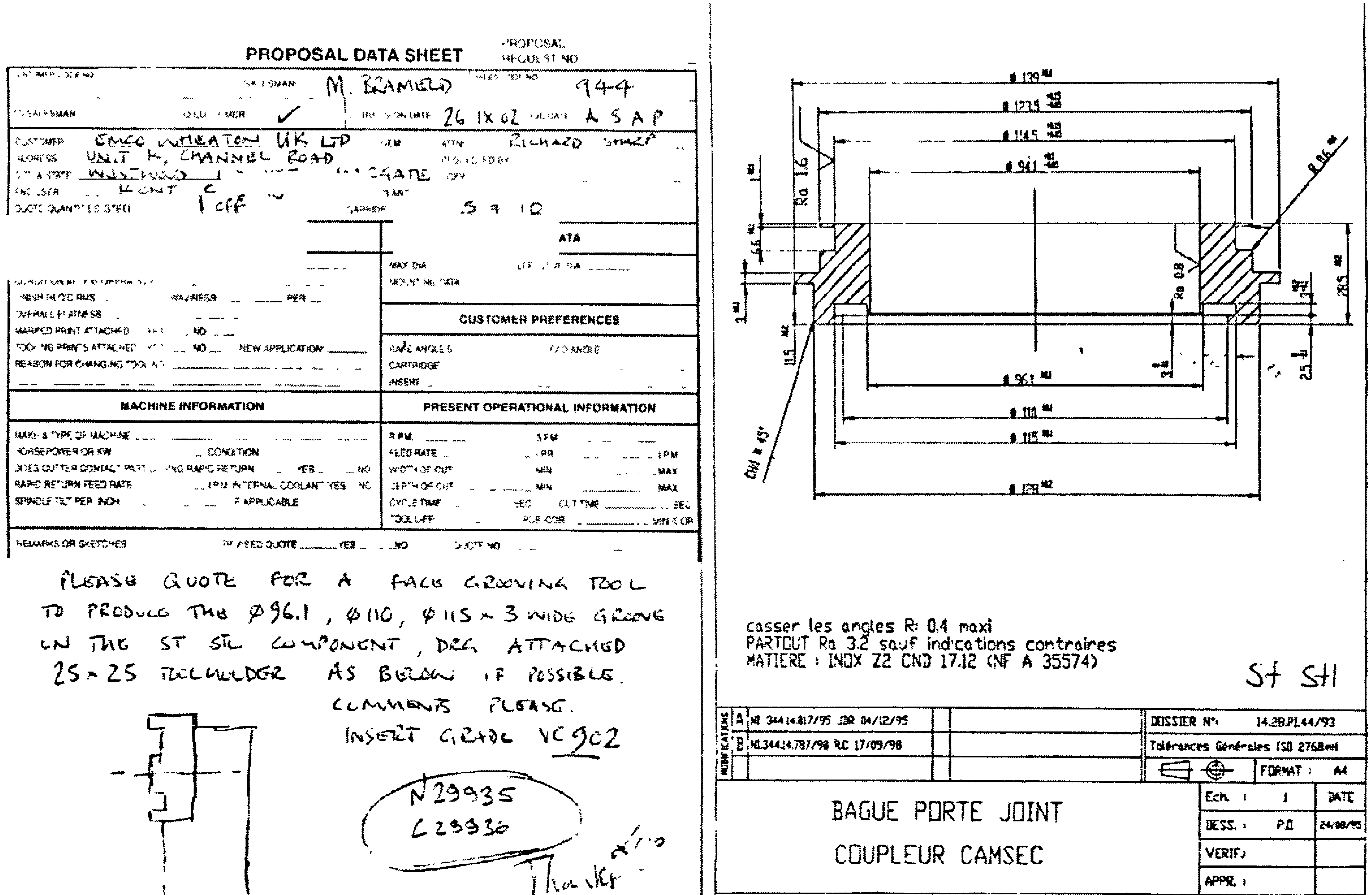


Figure C10: Proposal form and workpiece drawing for case three: special grooving cutter.

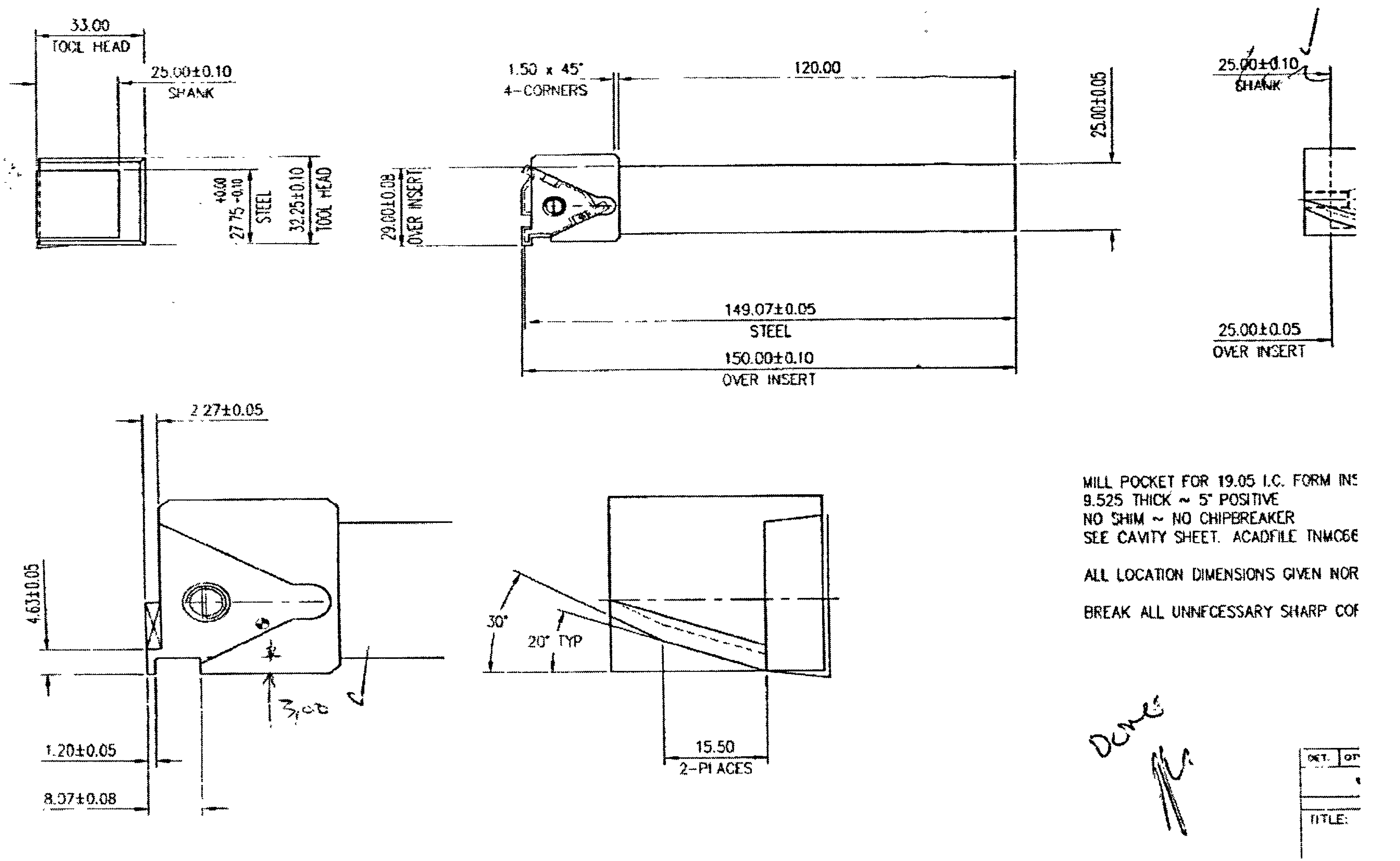


Figure C11: Design for case three: special grooving cutter.

Table C2: Ontology framework for case three: special grooving cutter.

Ontology Element	Description of Value	Explanation
Component	Workpiece	The workpiece has an unusual groove in its face that require machining.
Function	Gain Shape	By machining the face groove it will gain the required shape.
Sub-function	Workpiece	As the focus of the design is at the face groove the design consideration are made toward the workpiece.
Design Considerations		
Workpiece Material	Steel	There are many varieties of steel with a varied array of properties. An aircraft grade steel could not be machined with this insert – it would simply break. The steel grade given is suitable to be cut with this insert.
Cost	£110	This was the cost of producing the cutting tool for the customer.
Surface Finish	Finish	The customer requires a finished surface.
Workpiece Shape & Size	Overall diameter = 128mm Thickness = 28.5mm Groove to be cut = 96.1mm to 115mm with lip at 110mm	The area of interest for the designer is the dimension of the groove to be cut. It is a face-grooving tool that is required to cut the groove as required.
Tool/Material Selection	Yes	The area in which the cutting tool has to operate is very small therefore a small insert is required. A consideration has to be as to whether an insert shape can be found to machine the feature. Having found the insert we have to see if the insert is not too weak because of the clearances required. This is a special insert form ground from a standard insert. The material is steel (see below for material).
Customer	Given	The customer name is given but for confidentiality reasons it is not possible to show in this research. The customer name is important to identify firstly who is the design work for and then to begin to design for that customer.
Workpiece Name	Not given	A design drawing is given with the illustrating the groove to be cut but a name is missing from the drawing.

Ontology Element	Description of Value	Explanation
Component	Insert	Also here as there is an unusual groove to be cut that poses selection problems for the insert choosing functions based on the insert seemed applicable.
Function	Reduce Tool-Life	The small size of the cutter means it is liable to easy breakage and hence a reduction in its tool life.
Sub-function	Surface Finish	Surface finish is also important for the customer so the selection of design considerations based surface finish.
Design Considerations		
Workpiece Material	Steel	There are many varieties of steel with a varied array of properties. An aircraft grade steel could not be machined with this insert – it would simply break.
Machine Tool	NC machine	The NC machine can accommodate many sizes of tool.
Insert Type	Special Insert	A special insert made from TNMC66-SP.
Through Coolant	No	Though coolant not required for this job. Coolant will be applied externally on the NC lathe as appropriate.
Speeds	Not considered	These were considered to be well within the range of the NC machine that the cutting to was to operate on.
Feedrate	Not considered	These were considered to be well within the range of the NC machine that the cutting to was to operate on.
Depth of Cut	3mm	The depth of the groove.
Ontology Element	**Description of Value**	**Explanation**
Component	Toolholder	A special toolholder has been designed for this design therefore it was appropriate that the design be recorded on the basis of a third item being the toolholder.
Function	Holds Insert	It is required to hold a special insert.
Sub-function	Standard Features	Even though the design of the toolholder is a special, the toolholder still has identifiable standard features.
Design Considerations		
Seat Area	See Cavity Sheet: ACADFILE TNMC66-SP	Mill pocket for 19.05 I.C. from insert. 9.525 thick ~ 5° positive. No shim ~ No chip breaker.
Seat/Insert Clearance	No shim, clearance angles	There is no shim required as it can't be fitted in because of the material being cut there can be no damage to the toolholder. The clearance angles were considered, as there is limited space to work in and out of, the cutting tool must be able to engage and disengage without fouling the workpiece.
Slots/Cut-outs/Holes	Hole for the insert screw	No clamps necessary as the space available is very tight and a clamp would obstruct the machining process.

C9 VALIDATION PHASE ONE: QUESTIONNAIRE TO RATE TERMS IN THE ONTOLOGY FRAMEWORK

C9.1 Participant profile

All answers to questionnaire will remain strictly confidential. This information in only intended for analysis of user profile.

1. User Name:
2. How long have you been involved in the cutting tool industry? **(Please indicate)** ________ years
3. Please indicate what role/s have you carried during this time?
4. Do you have qualifications in one or more of the following:
    a. Mechanical Engineering
    b. Manufacturing
    c. Process Engineering
    d. Experience of the above
5. If so, to what level?

C9.2 Cutting tool system

The following are considered to be the main components within a cutting tool system. Please indicate on a scale 1 – 6 the degree to which you agree with the concepts of the cutting tool system.

Scale: 1 indicates that you strongly disagree with the component proposed, and a rating of 6 indicates that you strongly agree with the component proposed.

Note: If you disagree with one of the following please indicate by writing below the box what you would prefer instead.

Toolholder

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Clamping system

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Insert

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Component

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

C9.3 Base-functions

The following are the functions that describe the cutting tool system. Please indicate on a scale 1 – 6 the degree to which you agree with the functions of each component within the cutting tool system.

Scale: 1 indicates that you strongly disagree with proposed function. A rating of 6 indicates that you strongly agree with the proposed functions.

Note: If you disagree with one of the following please indicate by writing below the box what you would prefer instead.

Holds Insert

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Transmits Force

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Protect Pocket

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Locks Insert

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Reduce Tool Life

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Remove Material

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Produce Shape

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Attain Quality

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Gain Shape

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Increase Value

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

C9.4 Meta-functions

Instructions for this part of the questionnaire:

Study the meta-functions described by the researcher and assess and score the table below.

The following are the meta-functions that describe the base-functions within the cutting tool system described above. Please indicate on a scale 1 – 6 the degree to which you agree with the meta-functions of each component within the cutting tool system.

Scale: 1 indicates that you strongly disagree with proposed function. A rating of 6 indicates that you strongly agree with the proposed functions.

Note: If you disagree with one of the following please indicate by in the space below what you would prefer instead.

			Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
Number	Type	Description	1	2	3	4	5	6
M1	Enhance	To enhance the production of shape						
M2	Enhance	To enhance the removal of material						
M3	Enable	To enable the production of shape						
M4	Enable	To enable force to be transmitted						
M5	Prevent	To prevent a decrease in tool life						
M6	Enable	To enable contact with component						
M7	Control	To control the reduction in tool life						
M8	Prevent	To prevent deterioration in shape						
M9	Control	To control the achieving of quality						
M10	Control	To control the achieving of quality						
M11	Enable	To enable the achievement of quality						
M12	Control	To control the gain in shape						
M13	Enable	To enable an increase in value						
M14	Drive	To drive the gain in shape						
M15	Improve	To improve the increase in value						
M16	Drive	To drive the increase in tool life						

C9.5 Ways of achievement

Instructions for this part of the questionnaire:

Step 1: Study the diagrams of the behaviours or 'ways of achievement' described by the researcher.

Step 2: Assess and score each table below.

Scale: 1 indicates that you strongly disagree with proposed behaviour. A rating of 6 indicates that you strongly agree with the proposed behaviour.

Note: If you disagree with one of the following please indicate by writing below the box what you would prefer instead.

Firm Support

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Standard Features

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Continuous Contact

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Geometry of Pocket

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Machine Attachment

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Shim

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Cartridge

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Cutting Pressure

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Screw & Clamp

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Cartridge

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Surface Finish

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Component Tolerances

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Cutting Force

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Dimensional Change to Component

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Heating of Component

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Power Requirement

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Chip Formation

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Required Finish

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Desired Shape or Size

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Boring

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Turning

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Drilling

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Trepanning

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Grooving

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Milling

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Surface Finish

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Dimensional Accuracy

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Shape & Size

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Application

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Tool

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Component

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Operation/Process

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Performance

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

Cost

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

C10 VALIDATION PHASE TWO: QUESTIONNAIRE FOR CASE STUDIES

Please follow the instructions below on how to complete this questionnaire:

Study each of the cases (proposal form and design provided) and the provided cutting tool design framework material

Study the prepared the three case tables compare the entered values given in the table with your own assessment by cross checking from the design proposal information and design given.

Assess and score the tables below to how well you feel the cases represent the given questions

Please indicate on a scale 1 – 6 (see below for rating) the degree to which you agree with the following statements by placing a tick (v) in the appropriate box.

1 = Strongly Disagree
2 = Disagree
3 = Slightly Disagree
4 = Slightly Agree
5 = Agree
6 = Strongly Agree

Case Study One: T-Slot Milling Cutter

Criteria	1	2	3	4	5	6	
Adequacy							The case study represents with acceptable quality the knowledge in cutting tool design
Coherence							This case study presents the knowledge in cutting tool design in a logical and consistent manner
Completeness							This case reflects completely the necessary parts to make the framework for cutting tool design representation
Soundness							The framework is a sound representation of knowledge in cutting tool design
Usefulness							The framework will be useful for practical cutting tool design

Case Study Two: E-Z Set Cutter

Criteria	1	2	3	4	5	6	
Adequacy							The case study represents with acceptable quality the knowledge in cutting tool design
Coherence							This case study presents the knowledge in cutting tool design in a logical and consistent manner
Completeness							This case reflects completely the necessary parts to make the framework for cutting tool design representation
Soundness							The framework is a sound representation of knowledge in cutting tool design
Usefulness							The framework will be useful for practical cutting tool design

Case Study Three: Special Grooving Cutter

Criteria	1	2	3	4	5	6	
Adequacy							The case study represents with acceptable quality the knowledge in cutting tool design
Coherence							This case study presents the knowledge in cutting tool design in a logical and consistent manner
Completeness							This case reflects completely the necessary parts to make the framework for cutting tool design representation
Soundness							The framework is a sound representation of knowledge in cutting tool design
Usefulness							The framework will be useful for practical cutting tool design

Any additional comments on the framework for representing cutting tool design knowledge. (Please comment below)

APPENDIX D

Implementing a viewpoint of design reuse

D1 DOMAIN KNOWLEDGE

The author as described in section 7.2.4 of chapter seven of how he obtained the domain knowledge illustrated in the tables D1 to D4. The values for the 'Symbol' or 'Boolean' types are not given here as they are numerical or a 'yes/no'. For example, cost of tool: £240 or diameter of tool: 18mm (see section 7.2.4). Also for confidentiality the customer names are left out of this appendix.

Table D1: Domain Knowledge: milling types

Milling types				
Back Facing Cutter	Drill	Grooving Cutter	Scallop Cutter	Spot facing Cutter
Ball Nose Cutter	End Mill	Half Side & Face Cutter	Side	Square Shoulder Mill
Barrel Cutter	End Mill & Chamfer Tool	Half Side Mill	Side & Face Cutter	Step Cutter
Cartridge Face Mills	Face & Chamfer Mill	Helical Cutter	Side Mill	T-slot Mill
Cartridge Square Shoulder Mill	Face Form Tool	HVA Cutter	Slitting Saw	Tag Notch & Chamfer Bar
Center-Dex Cutter	Face Mill	Interpolation Cutter	Slot Mill	Thread Milling Cutter
Chamfering Mill	Facing Cutter	MILLING ASSEMBLIES	Slotting Cutter	Thrust Face Cutter
Circular Cutter	Flex-A-Dex Bar	Milling Cutter	Slotting End Mill	TopMill S
Circular Grooving Cutter	Flex-A-Dex Bar	Modified 'T'-Slot Cutter	Solid Hard metal	UTS-63 Shank Form Cutter
COMBINATION CUTTER	Form Cutter	Multi-tooth Square Shoulder Mill	Special Cutter	Val-U-Edge
Copy Mill	Face Form Tool	Nose Collar	Side & Face Cutter	Val-U-Mill
Counter Bore Cutter	Face Mill	Plunge Facing & Chamfering Tool	Side Mill	WELD PREP CUTTER

Table D2: Domain Knowledge: mounting types

Mounting types				
ABS 63	CAT45	DIN1835-B20	End Mill Adapters	Shell Mill Adapter
ABS40	Collet Chuck	DIN1835-B25	HSK-63	STANDARD S40 STYLE
ABS50	Combination shell mill adapters	DIN1835-B32	ISO 40 SHANK	UTS 50
ABS50-N	DIN 69871	DIN1835-B40	Keyway	UTS-63 Shank
BT30	DIN 69871-A50	DIN1835-B50	Machine Shaft	V40-ISO SHANK DIN 69871/1 FROM 'A'
BT40	DIN 69871/1 FORM 'A'	DIN1835-E20	Morse Taper Adapters	VTS 40
BT50	DIN 69893 FORM-A	DIN1835-E32	PTMR	VTS 40 SOCKET
	DIN1835 FORM "E"	DIN1835/1 FORM B & D	Rotaflex Shank	VTTS 40
	DIN1835-A16	DOUBLE LOCK	S16	Weldon Shank

Table D3: Domain Knowledge: insert types

Insert Types					
222 79 500 ...	GEOMETRY M	SDHN	SPEN	TNMM	VLGP
222. 79. 5	GEOMETRY U	SDHW	SPEW	TOHX	VLR
222.79.500.76	HNGX	SDMT	SPG-422	TOMX	VLRP
222.79.501...	LPGX	SDMW	SPHN	TPAN	VLS
235.06.602...	MDHW	SDNT	SPHW	TPAX	VLT
4P ACME	MDHX	SEAN	SPHX	TPGA	VLTC
BDNT	PCD	SEC 633J	SPKN	TPGN	VLTK
BONT	RCMT	SECW	SPKR	TPJN	VLTP
CCGT	RCMT-X	SEE INSERT DWG.	SPMT	TPKN	WCEM
CCMT	RCMX	SEKN	SPMW	TPKR	WCGT
CCMW	RD	SEKR	SPNT	TPMC	WCMT
CDEW	RDHT	SMDW	SPNX	TPMT	WNMG
CNMG	RDMT	SNKT	TCAX	TPMW	XDHT
CNMM	RDMW	SNMG	TCMW	TPUN	XPET
CPGT	RNMG	SNMG	TEGW	VBMT	XPHT
CPGW	RPMT	SNMM	TNAX	VCGT	XPNT
CPMW	RPMW	SNMT	TNEC	VLA	
CPNT	SCMT	SPAN	TNGW	VLAS	
DCMT	SCMW	SPE	TNHX	VLB	
DNMG	SD-12P	SPE-325	TNLN	VLER	
DNMM	SD-322P	SPEC	TNMC	VLF	
EOHX	SD-422P	SPECIAL INSERT	TNMG	VLG	

Table D4: Domain Knowledge: workpiece material types

Workpiece material types			
708M40	Carbon Steels	Lead Bronze	S. G. Iron
Alloy Steel	Cast Iron	Non-ferrous Alloys	Sintered Iron
Aluminium	Cast Steel	Phosphorus Bronze	Stainless Steel
BS970 605M36	High Temperature Alloys	RESIN	Steel
			Titanium

D2 CASES FOR VALIDATION

Case Two

In this case both the proposal forma and the workpiece drawing is given together with some written notes, these are shown in figures D1 & D2 respectively. This is a proposal for several tools to work on the same component. For this case the tool to be searched is a thrust face cutter, the design is shown in figure D3. A summary of the information within the case base for this proposal and design is shown in table D5.

Table D5: The values within the case base for case two.

Attribute on CBR	Extracted term (Attribute value)
Cost of Tool	£260
Customer Name	Nissan
Drawing No.	S25271
Component Material	Aluminium
Component Name	Cylinder Head
Feature to be Cut	Thrust Face
Finishing	Yes
Machine Type	CNC Milling Machine
Mounting	Keyway
Roughing	No
Through Coolant	No
Depth of Cut	1mm
Diameter of Tool	52mm
Insert Material	Carbide
Insert Type	CPMW
Length of Tool	9mm
Milling Type	Val-U-Mill

Case Three

Case three both the proposal form and the workpiece drawing are given. These are presented in figures D4 & D5 respectively. The associated design for this proposal is shown figure D6. The values entered for the attributes in the case base by the author when creating this case are shown in table D6.

Table D6: The values within the case base for case three.

Attribute on CBR	Extracted term (Attribute value)
Cost of Tool	£230
Customer Name	ALBON
Drawing No.	S28346
Component Material	Cast Iron
Component Name	Flywheel
Feature to be Cut	37.5 radius Slot
Finishing	Yes
Machine Type	CNC Milling Machine
Mounting	Keyway
Roughing	No
Through Coolant	No
Depth of Cut	1mm
Diameter of Tool	75mm
Insert Material	Carbide
Insert Type	SPE-325
Length of Tool	9mm
Milling Type	Val-U-Mill

The customer would like a new style of cutter to produce the 37.3 radius groove in the flywheel. In this case an indexable solution cutter is required. The design is an arbour (keyway) mounted tool as shown in figure D6.

Case Four

A written proposal is given to the designer with a drawing of an insert that is currently being used to machine the workpiece. The customer wants an alternative solution that will reduce cost and improve tool-life. The requirement from the cutting tool is to machine the flash from the workpiece. The proposal and the workpiece drawing are given in figures D7 & D8 respectively. The case base file for this case has the following values entered, as shown in table D7. These can be entered on the CBR query field and this design would result with a similarity of 1.0. The design that is the result of the design activity is shown in figure D9. It shows a new insert and a toolholder that is required to hold the insert.

Case Five

This is the only case where only the proposal form is given to the designer to design the cutting tool. This is shown in figure D10. In this case the salesperson just requires the designer to call up a previous design and resize according producing a concept drawing. This case shows a good example of the type of reuse activity within the domain. The recalled design is shown in figure D11.

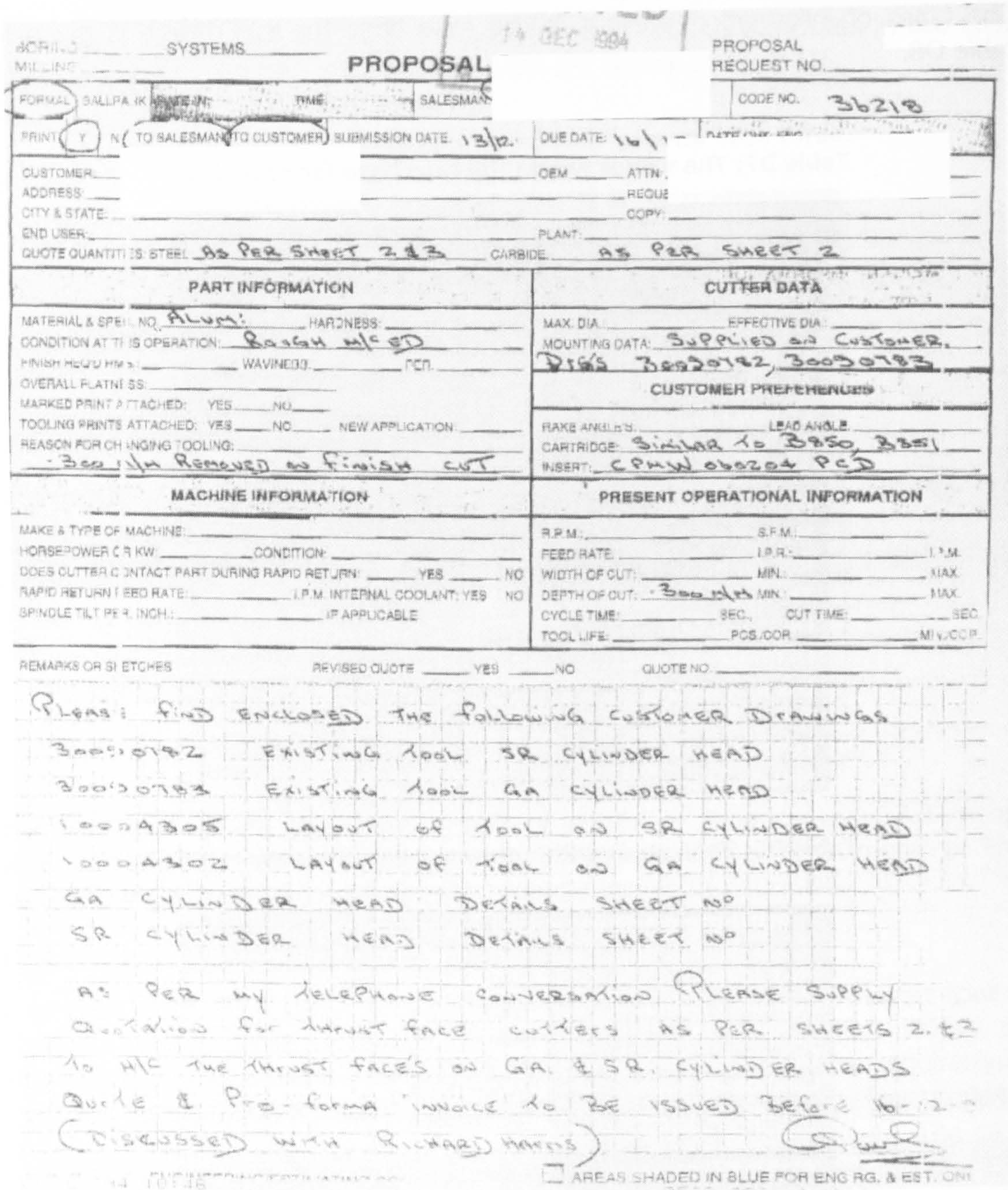
The types of information present in the case base for this design is given in table D8.

Table D7: The values within the case base for case three.

Attribute on CBR	Extracted term (Attribute value)
Cost of Tool	£280
Customer Name	CUTTING TOOL SUPPLIES
Drawing No.	T29308
Component Material	Titanium
Component Name	Artificial Joint
Feature to be Cut	Casting Flash
Finishing	Yes
Machine Type	CNC Milling Machine
Mounting	DIN1835-B25
Roughing	No
Through Coolant	No
Depth of Cut	1mm
Diameter of Tool	19mm
Insert Material	Carbide
Insert Type	TPGN
Length of Tool	90mm
Milling Type	Milling Cutter

Table D8: The values within the case base for case three.

Attribute on CBR	Extracted term (Attribute value)
Cost of Tool	£250
Customer Name	FORD
Drawing No.	D27636
Component Material	Aluminium
Component Name	Cylinder Block
Feature to be Cut	Cylinder Bore
Finishing	Yes
Machine Type	Station 13 RH PUMA
Mounting	ABS32-N
Roughing	No
Through Coolant	Yes
Depth of Cut	1mm
Diameter of Tool	12.30mm
Insert Material	Carbide
Insert Type	CPMW
Length of Tool	45mm
Milling Type	Milling Cutter



14 DEC 1994

BORING ____ SYSTEMS ____
MILLING ____

PROPOSAL

PROPOSAL REQUEST NO. ____

FORMAL / BALLPARK / QUOTE IN: ____ TIME: ____ SALESMAN: ____ CODE NO. 36218

PRINT (Y) N (TO SALESMAN / TO CUSTOMER) SUBMISSION DATE 13/12. DUE DATE 16/1 – DATE ____

CUSTOMER: ____ OEM ____ ATTN: ____
ADDRESS: ____ REQUE____
CITY & STATE: ____ COPY: ____
END USER: ____ PLANT: ____
QUOTE QUANTITIES: STEEL AS PER SHEET 2 & 3 CARBIDE AS PER SHEET 2

PART INFORMATION	CUTTER DATA
MATERIAL & SPEC. NO. ALUM: HARDNESS: ____	MAX. DIA. ____ EFFECTIVE DIA. ____
CONDITION AT THIS OPERATION: ROUGH M/C ED	MOUNTING DATA: SUPPLIED ON CUSTOMER DRG'S 30030782, 30030783
FINISH REQ'D RMS: ____ WAVINESS ____ PCN ____	CUSTOMER PREFERENCES
OVERALL FLATNESS: ____	RAKE ANGLES: ____ LEAD ANGLE ____
MARKED PRINT ATTACHED: YES ____ NO ____	CARTRIDGE: SIMILAR TO B850, B851
TOOLING PRINTS ATTACHED: YES ____ NO ____ NEW APPLICATION ____	INSERT: CPMW 060204 PCD
REASON FOR CHANGING TOOLING: – 3mm M/M REMOVED ON FINISH CUT	

MACHINE INFORMATION	PRESENT OPERATIONAL INFORMATION
MAKE & TYPE OF MACHINE: ____	R.P.M.: ____ S.F.M.: ____
HORSEPOWER OR KW: ____ CONDITION: ____	FEED RATE: ____ I.P.R.: ____ I.P.M.
DOES CUTTER CONTACT PART DURING RAPID RETURN: ____ YES ____ NO	WIDTH OF CUT: ____ MIN.: ____ MAX.
RAPID RETURN FEED RATE: ____ I.P.M. INTERNAL COOLANT: YES NO	DEPTH OF CUT: 3mm M/M MIN.: ____ MAX.
SPINDLE TILT PER INCH: ____ IF APPLICABLE	CYCLE TIME: ____ SEC. CUT TIME: ____ SEC.
	TOOL LIFE: ____ PCS./COR ____ MIN./COR

REMARKS OR SKETCHES REVISED QUOTE ____ YES ____ NO QUOTE NO. ____

PLEASE FIND ENCLOSED THE FOLLOWING CUSTOMER DRAWINGS

30030782 EXISTING TOOL SR CYLINDER HEAD
30030783 EXISTING TOOL GA CYLINDER HEAD
1000A305 LAYOUT OF TOOL ON SR CYLINDER HEAD
1000A302 LAYOUT OF TOOL ON GA CYLINDER HEAD
GA CYLINDER HEAD DETAILS SHEET NO
SR CYLINDER HEAD DETAILS SHEET NO

AS PER MY TELEPHONE CONVERSATION PLEASE SUPPLY QUOTATION FOR THRUST FACE CUTTERS AS PER SHEETS 2 & 3 TO M/C THE THRUST FACES ON GA & SR CYLINDER HEADS. QUOTE & PRO-FORMA INVOICE TO BE ISSUED BEFORE 16-12-

(DISCUSSED WITH RICHARD HARRIS)

☐ AREAS SHADED IN BLUE FOR ENG RG. & EST. ONLY

Figure D1: Case two proposal form.

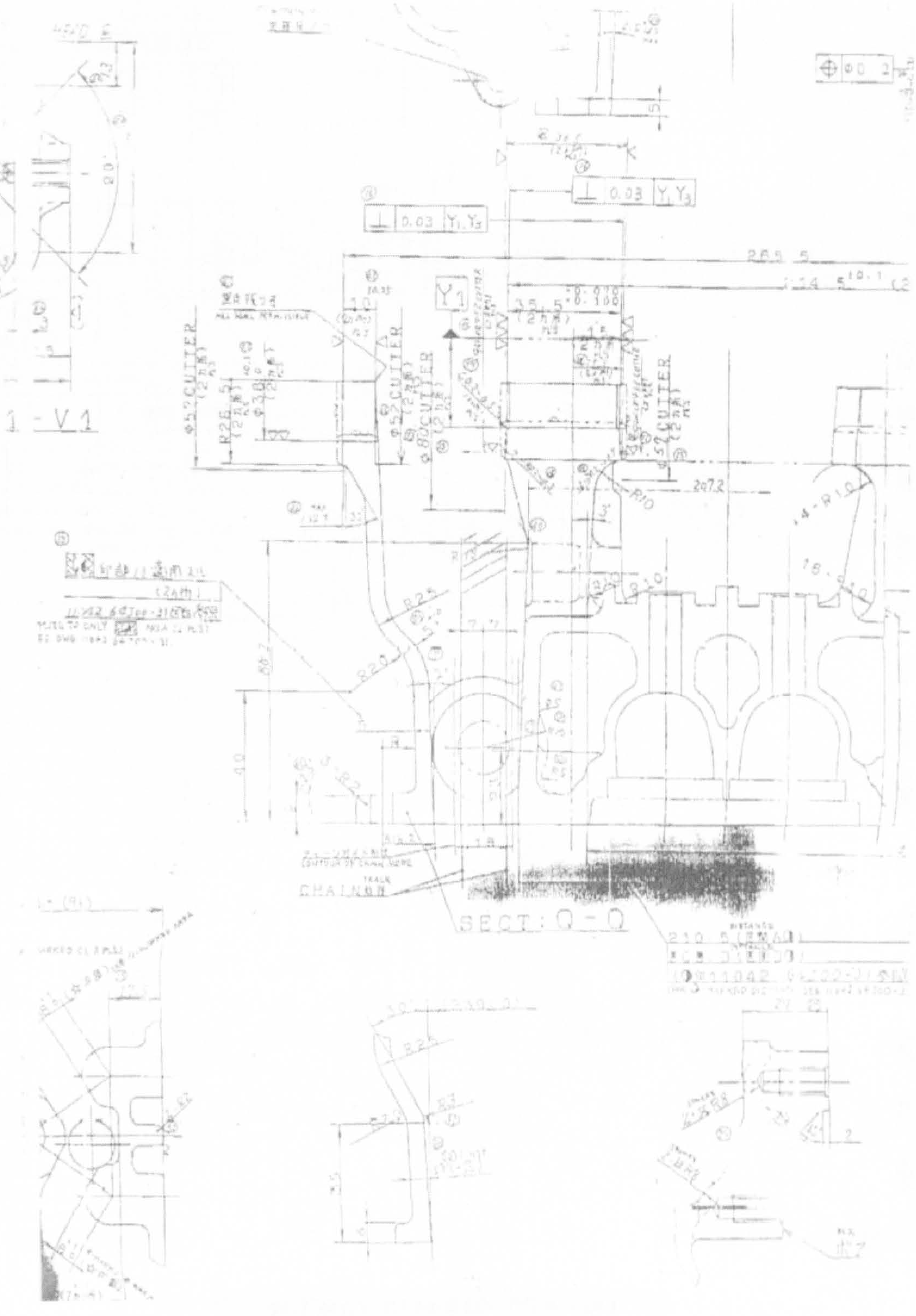


Figure D2: Case two workpiece drawing.

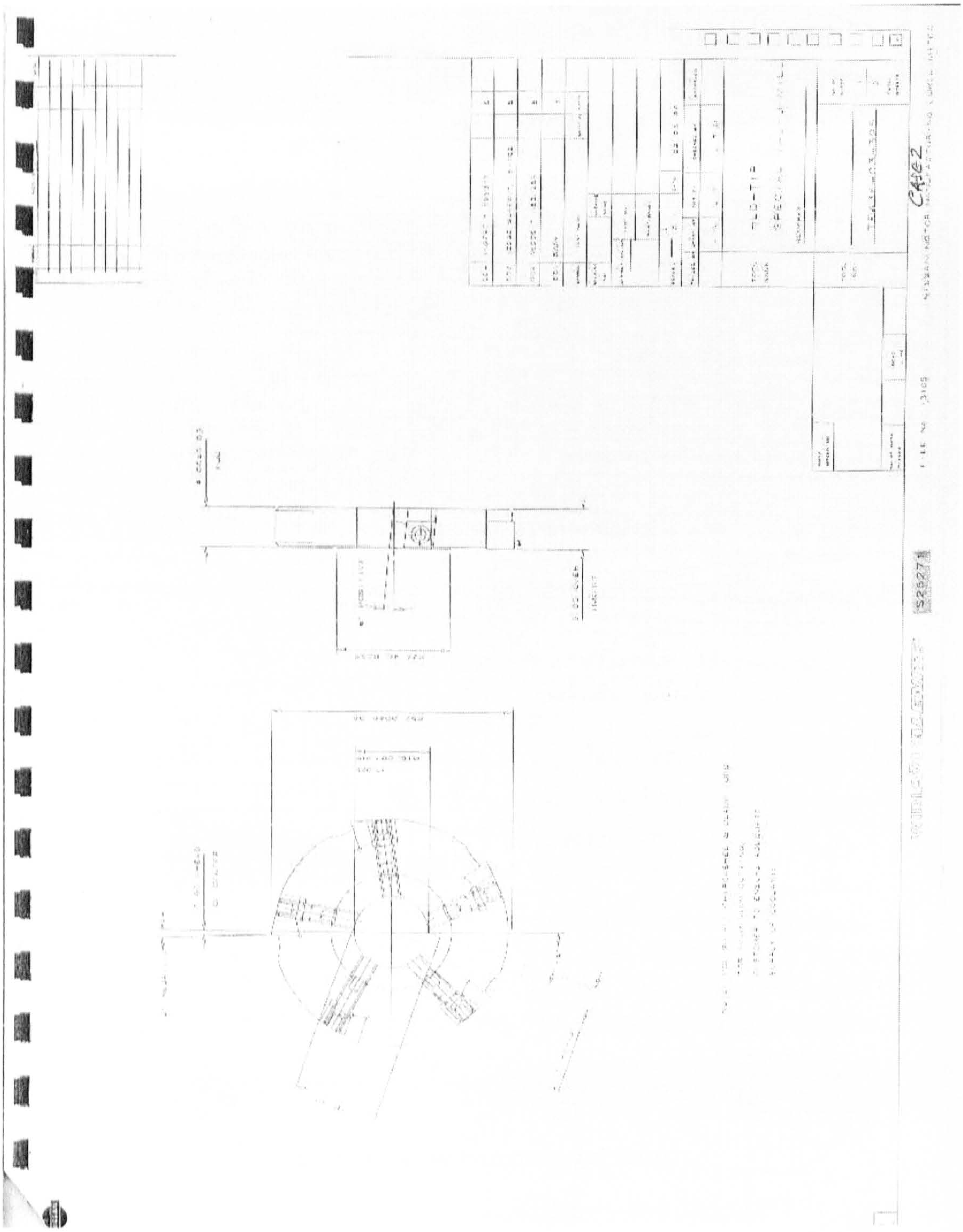


Figure D3: Design for case two.

348864 R B F INCORPORATED (517) 323-3181

PROPOSAL DATA SHEET

PROPO REQUEST NO ______

CUSTOMER CODE NO.	SALESMAN:	SALES CODE NO. 944
TO SALESMAN	TO CUSTOMER ✓	SUBMISSION DATE 13: III : 00 — DUE DATE 26: III : 00

CUSTOMER: ______ ATTN: ______
ADDRESS: ______ REQUESTED BY: ______
CITY & STATE: ______ COPY: ______
END USER: ______ PLANT: ______
QUOTE QUANTITIES: STEEL 1 & 2 OFF CARBIDE: ______

PART INFORMATION	CUTTER DATA
MATERIAL & SPEC. NO. ______ HARDNESS: ______	MAX. DIA.: ______ EFFECTIVE DIA.: ______
CONDITION AT THIS OPERATION: ______	MOUNTING DATA: ______
FINISH REQ'D RMS ______ WAVINESS: ______ PER ______	
OVERALL FLATNESS: ______	**CUSTOMER PREFERENCES**
MARKED PRINT ATTACHED: YES ___ NO ___	
TOOLING PRINTS ATTACHED: YES ___ NO ___ NEW APPLICATION ______	RAKE ANGLE'S ______ LEAD ANGLE: ______
REASON FOR CHANGING TOOLING: ______	CARTRIDGE: ______
	INSERT: ______

MACHINE INFORMATION	PRESENT OPERATIONAL INFORMATION
MAKE & TYPE OF MACHINE ______	R.P.M. ______ S.F.M. ______
HORSEPOWER OR KW: ______ CONDITION: ______	FEED RATE ______ I.P.R. ______ I.P.M.
DOES CUTTER CONTACT PART DURING RAPID RETURN ______ YES ______ NO	WIDTH OF CUT ______ MIN. ______ MAX.
RAPID RETURN FEED RATE ______ I.P.M. INTERNAL COOLANT YES NO	DEPTH OF CUT ______ MIN. ______ MAX.
SPINDLE TILT PER INCH ______ IF APPLICABLE	CYCLE TIME ______ SEC. CUT TIME ______ SEC.
	TOOL LIFE ______ PCS./COR. ______ MIN./COR.

REMARKS OR SKETCHES REVISED QUOTE ______ YES ______ NO QUOTE NO. ______

THEY ARE USING A H.S.S. CUTTER TO PRODUCE THE 37,5 RAD SLOTS – 1 AT $14^{+0,1}_{-0}$ & 1 AT $13^{+0,1}_{-0}$ WITH 5 RAD $^{+0}_{-3}$ ON I4 FLYWHEEL

THE WOULD LIKE AN INDEXABLE SOLUTION CUTTER TO HAVE ⌀27 BORE TO SUIT EXISTING ARBOR CAN WE PRODUCE A FIXED POCKET VERSION OF THE M900 WITH A 2,5 RAD INSERT?

INCOMPLETE REQUESTS WILL NOT BE PROCESSED

Figure D4: Proposal from for case three.

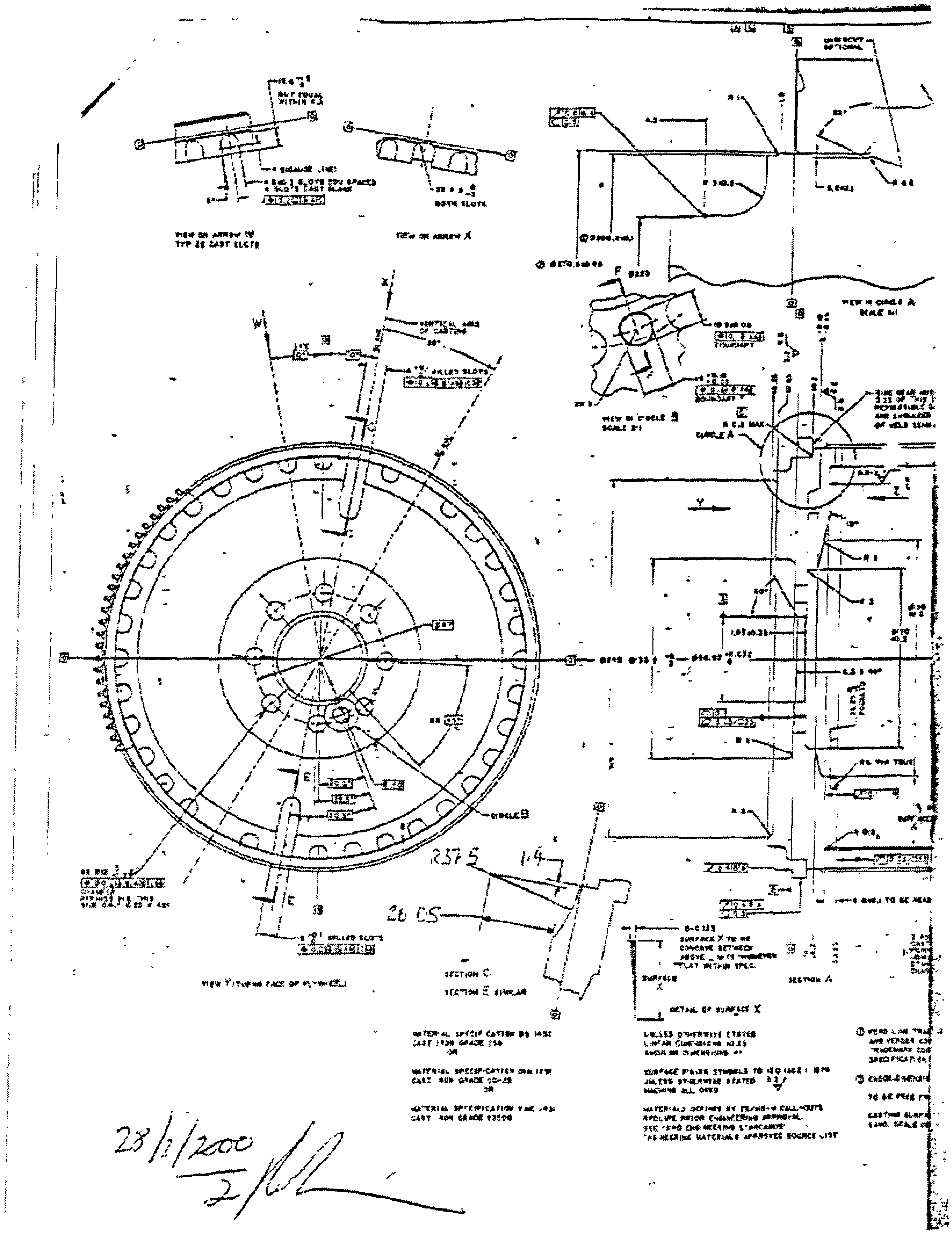


Figure D5: Workpiece drawing for case three.

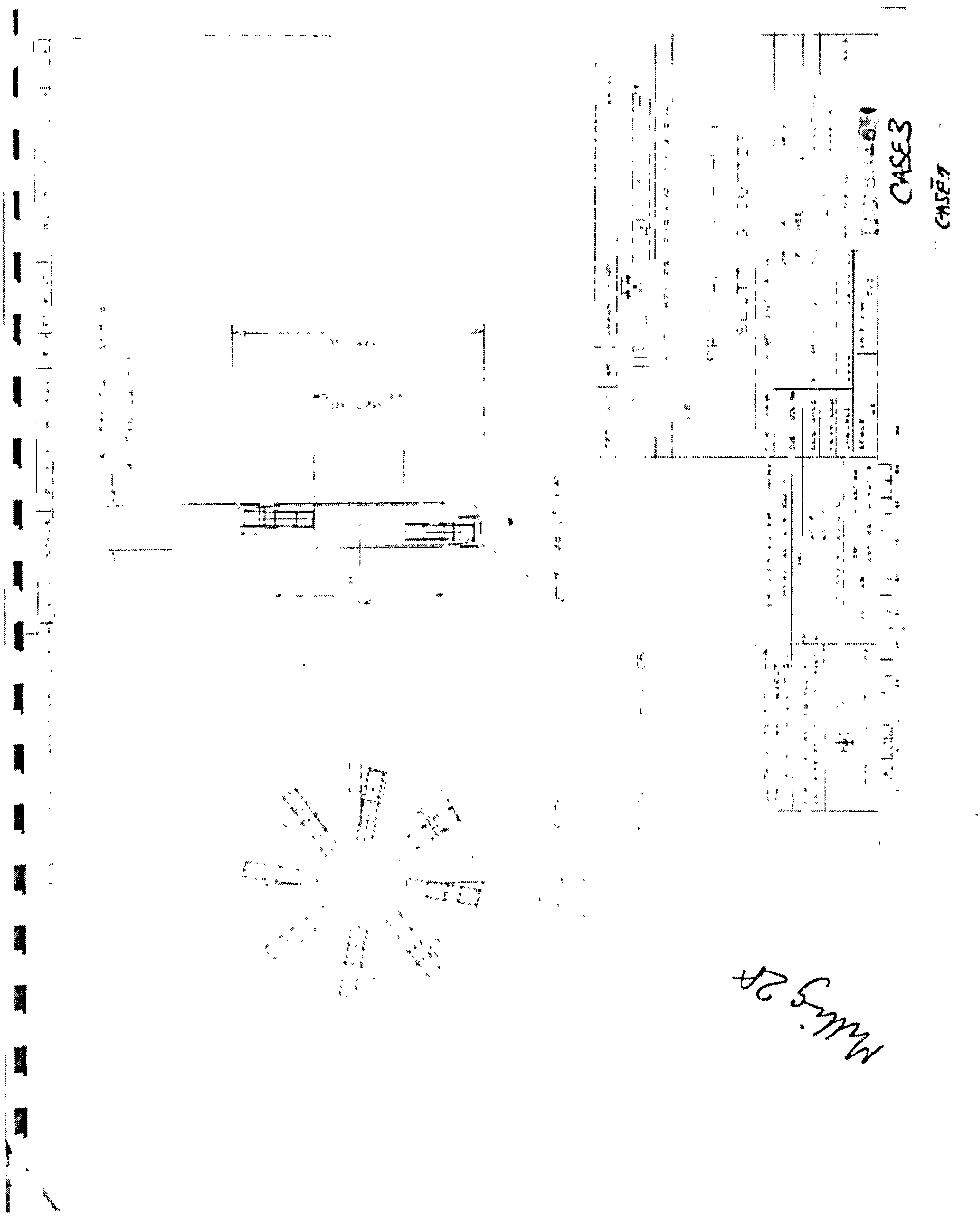


Figure D6: The design for case three.

To_Main Fax Widia Valenite 03/08/01 9 33 48 Page 1 of

WidiaValenite™
Metalcutting Tools & Fluids

Fax

Widia Valenite UK 12 Alston Drive, Bradwell Abbey Ind Estate Milton Keynes MK13 8HA

Date :- 03/08/01 (2 Sheets)

Subject:-

From:- E-Mail:-

To :- Richard Harris

PLEASE FIND ATTACHED SKETCH OF A SPECIAL MILLING INSERT FROM IN LEEDS.

THIS INSERT REMOVES THE CASTING FLASH FROM THE STEM OF AN ARTIFICAL JOINT PRIOR TO MACHINING THE SERRATIONS

THE CUSTOMER SPENDS APPROX £52,000 / YEAR ON THIS INSERT AND WOULD LIKE TO REDUCE INSERT COST AND IMPROVE TOOLIFE, WOULD IT BE POSSIBLE TO GRIND THIS FORM ON A SPMW INSERT GRADE VC2 AND USE A CENTRE DEX MILLING CUTTER, POSSIBLY A 32 M/M DIAMETER.

THE 11 M/M DIMENSION OVER THE LENGTH OF THE RADIUS COULD BE REDUCED TO 8 M/M IF REQUIRED, BUT ALL OTHER DIMENSIONS REMAIN THE SAME.

Best Regards

Figure D7: Proposal for case four.

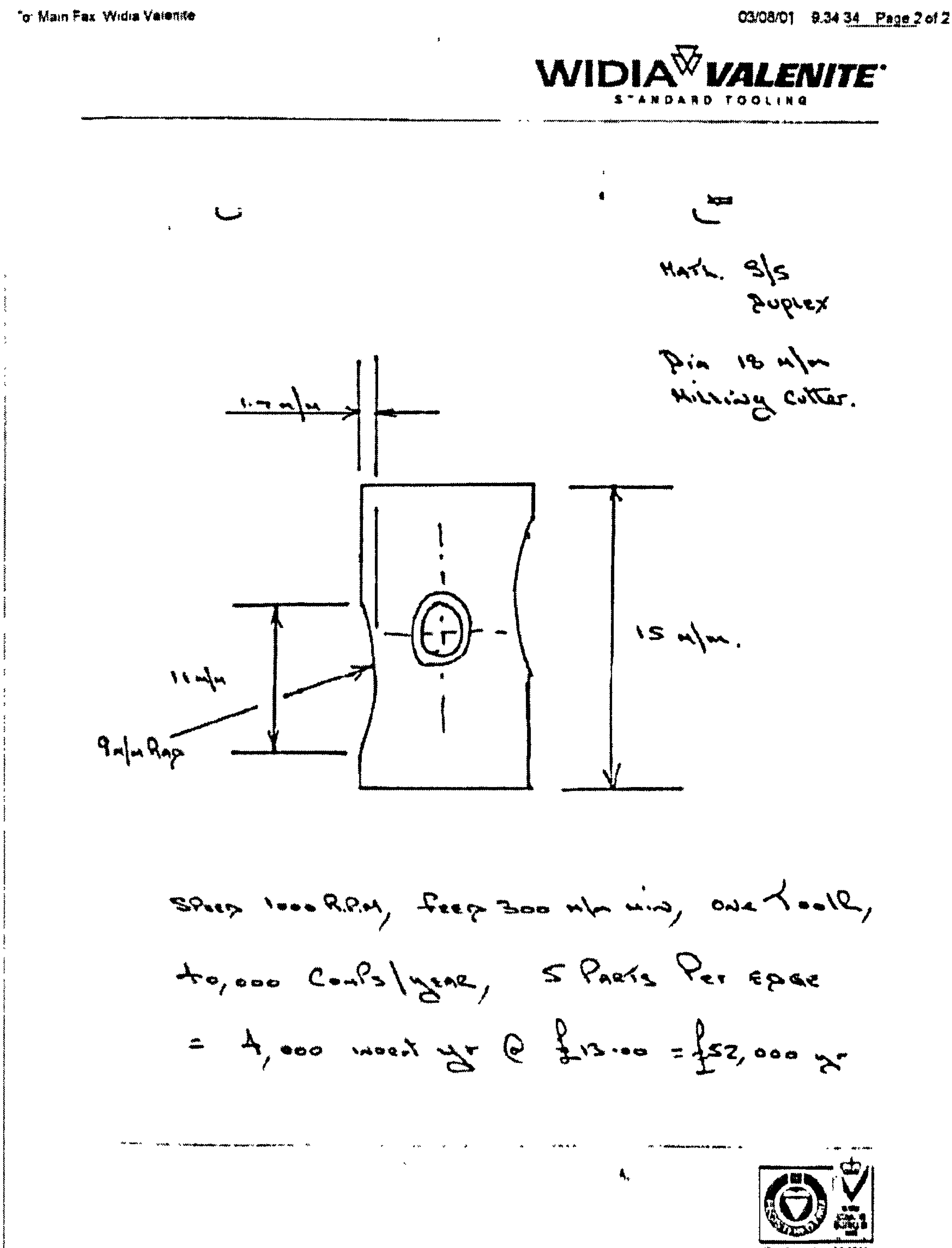


Figure D8: Insert drawing for case four.

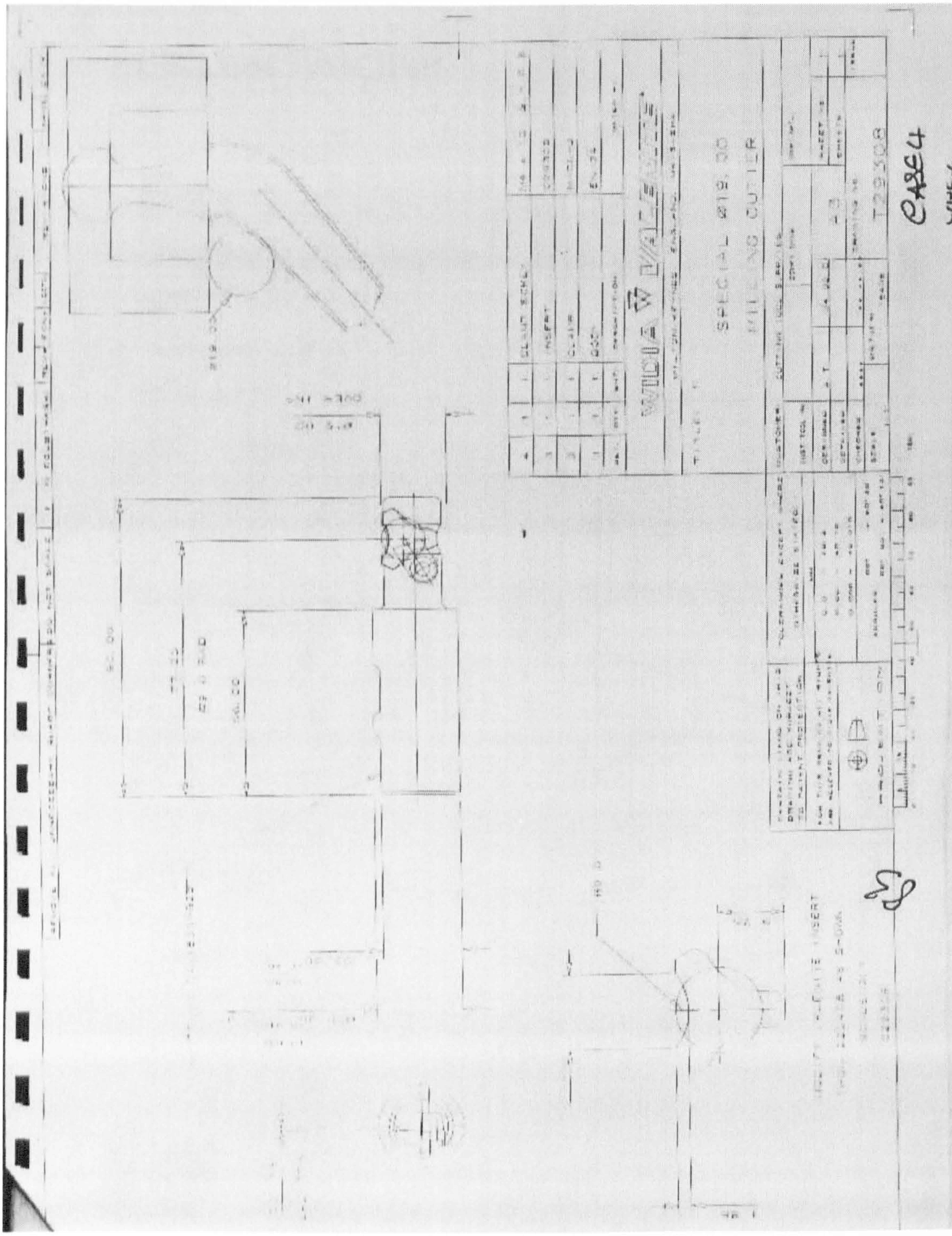
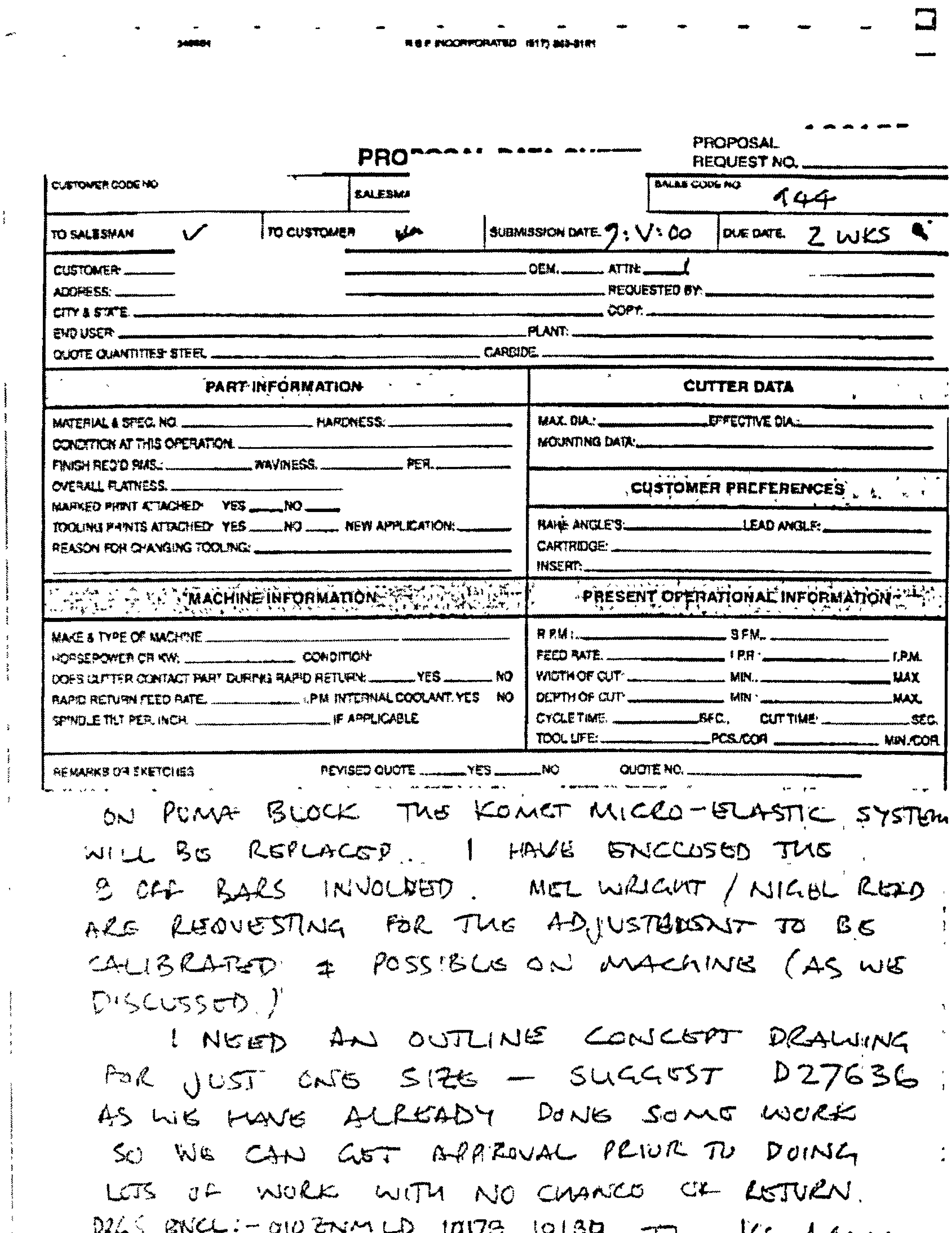


Figure D9: The design for case four.


PROPOSAL DATA SHEET
PROPOSAL REQUEST NO.
CUSTOMER CODE NO
SALESMAN
SALES CODE NO 144
TO SALESMAN ✓
TO CUSTOMER
SUBMISSION DATE 9 : V : 00
DUE DATE 2 WKS
CUSTOMER:
ADDRESS:
CITY & STATE
END USER
QUOTE QUANTITIES STEEL
OEM.
ATTN:
REQUESTED BY:
COPY:
PLANT:
CARBIDE

PART INFORMATION
MATERIAL & SPEC. NO. HARDNESS:
CONDITION AT THIS OPERATION
FINISH REQ'D RMS.: WAVINESS PER
OVERALL FLATNESS
MARKED PRINT ATTACHED: YES NO
TOOLING PRINTS ATTACHED: YES NO NEW APPLICATION:
REASON FOR CHANGING TOOLING:

CUTTER DATA
MAX. DIA.: EFFECTIVE DIA.:
MOUNTING DATA:

CUSTOMER PREFERENCES
RAKE ANGLE'S: LEAD ANGLE:
CARTRIDGE:
INSERT:

MACHINE INFORMATION
MAKE & TYPE OF MACHINE
HORSEPOWER OR KW: CONDITION:
DOES CUTTER CONTACT PART DURING RAPID RETURN: YES NO
RAPID RETURN FEED RATE. I.P.M. INTERNAL COOLANT. YES NO
SPINDLE TILT PER. INCH IF APPLICABLE

PRESENT OPERATIONAL INFORMATION
R.P.M.: S.F.M.
FEED RATE. I.P.R. I.P.M.
WIDTH OF CUT: MIN. MAX
DEPTH OF CUT: MIN. MAX.
CYCLE TIME: SEC. CUT TIME: SEC.
TOOL LIFE: PCS./COR MIN./COR

REMARKS OR SKETCHES
REVISED QUOTE YES NO
QUOTE NO.

ON PUMA BLOCK THE KOMET MICRO-ELASTIC SYSTEM WILL BE REPLACED. I HAVE ENCLOSED THE 3 OFF BARS INVOLVED. MEL WRIGHT / NIGEL REED ARE REQUESTING FOR THE ADJUSTMENT TO BE CALIBRATED & POSSIBLE ON MACHINE (AS WE DISCUSSED.)

I NEED AN OUTLINE CONCEPT DRAWING FOR JUST ONE SIZE — SUGGEST D27636 AS WE HAVE ALREADY DONE SOME WORK SO WE CAN GET APPROVAL PRIOR TO DOING LOTS OF WORK WITH NO CHANCE OF RETURN.

DRGS ENCL:- 010 ZNM LD 10173, 10130 [illegible] Thanks Norm

Figure D10: Case five proposal form.

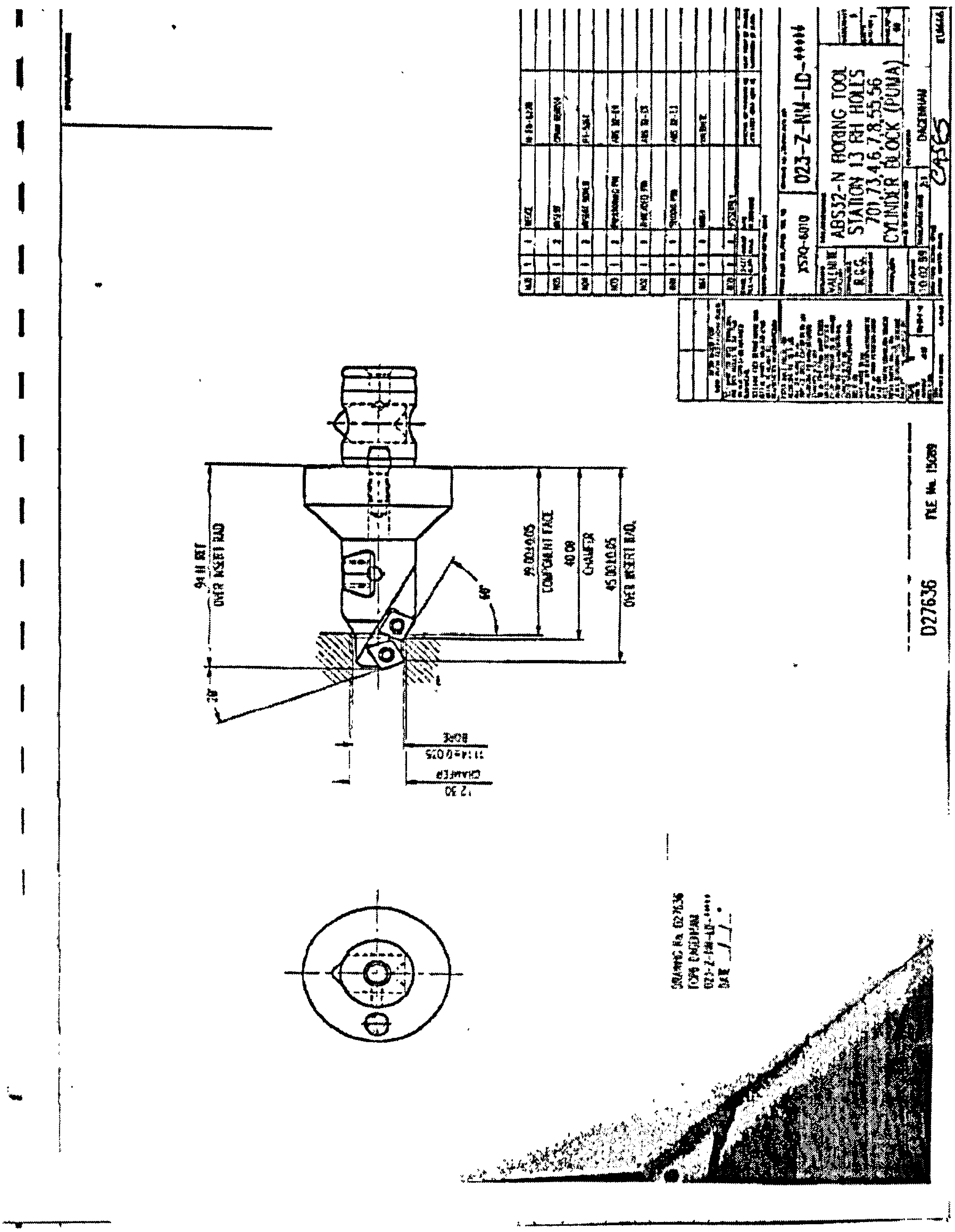


Figure D11: Recalled design – case five.

D3 VALIDATION OF THE VIEWPOINT OF DESIGN REUSE QUESTIONNAIRE

Section 1: User Profile

1. User Name: User One

2. Primary job role (Please tick one and state your role/position):

   - [X] Cutting Tool Design: **CHIEF ENGINEER**
   - [ ] Cutting Tool Sales:
   - [ ] Other:

3. How many years of cutting tool industry experience do you have (Please tick one)?

   - [ ] Less than 1 year
   - [ ] 1 year to 5 years
   - [ ] 5 years to 10 years
   - [ ] 10 years to 15 years
   - [ ] 15 years to 20 years
   - [X] More than 20 years

4. Have you ever used/tested a design reuse system before? [ ] Yes [X] No

   If yes, please expand and indication of level:

5. Please indicate your highest formal level of education (Please tick one):

   - [ ] Ordinary National Diploma
   - [X] Higher National Diploma
   - [ ] Graduate Level
   - [ ] Postgraduate
   - [ ] Other (Please indicate):

6. Please indicate your highest formal qualification background/type (Please tick one):

- [X] Engineering
- [ ] Manufacturing
- [ ] Management
- [ ] Commercial
- [ ] Other (Please indicate)

Section 2: Effectiveness of the viewpoint

Scenarios: You are presented with five cases that are represented as a viewpoint within the CBR Tool by a corresponding design. Each case includes the proposal form and corresponding component drawing, if available. Each design is represented on the CBR Tool by a set of attributes and associated values. For each attribute find a value from the proposal and component drawing, please record in the tables below for each case. These values will be entered at the retrieval interface on the CBR Tool.

Section 2a: Effectiveness for extracting terms for design cases

1. Please complete the table below with the values inputted for each case

Attribute	Case 1	Case 2	Case 3	Case 4	Case 5
Cost of Tool					
Customer Name	LUCAS	NISSAN		CUTTING TOOL SUPPLIES	FORD
Drawing No.					
Component Material					
Component Name					
Feature to be Cut					BORE & CHAMFER
Finishing					
Machine Type					
Mounting					ADAPTOR
Roughing					
Through Coolant					
Diameter of Tool	267	50	75	18	12
Insert Material					
Insert Type				SD-322P	
Length of Tool	13		14		45
Milling Type	GROOVING	HALF SIDE & FACE	GROOVING	FORM	

2. What were the most difficult attributes to obtain values for from the proposal and component drawings (Please tick as appropriate)?

Attribute		Reason for difficulty:
Cost of Tool	X	NOT FOUND ON PROPOSAL OR DESIGN, WOULD NEED TO BASE ON EXPERIENCE
Customer Name		
Drawing No.		
Component Material		
Component Name		
Feature to be Cut		
Finishing		
Machine Type		
Mounting		
Roughing		
Through Coolant		
Diameter of Tool	X	HARD TO FIND ON COMPONENT DRAWING
Insert Material		
Insert Type		
Length of Tool	X	NOT SPECIFIC FOR SLOTTING CUTTERS

3. Please record in the table below the similarity ratings for each design case retrieved

	Similarity for Retrieved Designs				
Query (Entered)	Design 1	Design 2	Design 3	Design 4	Design 5
Case 1	0.665	0.659	0.647	0.625	0.333
Case 2	0.5	0.497	0.497	0.477	0.477
Case 3	0.98	0.5	0.495	0.494	0.493
Case 4	0.499	0.496	0.486	0.333	0.319
Case 5	0.332	0.327	0.323	0.323	0.318

Have the right design or similar been found for all cases (Please tick one)? Yes [X] No [ ]

If no, any reason why not?

4. The cases used as scenarios are representative of the cutting tool design domain (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	**5**	6
Explain the reason for your choice:					

5. The attributes are appropriate for the viewpoint of cutting tool design reuse (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	**4**	5	6
Explain the reason for your choice: **SOME PARAMETER NEED EXPANDING E.G. MILLING, HALF SIDE & FACE CUTTER, SLOTTING ETC.**					

6. Capturing these attributes would improve our design searches (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	**6**
Explain the reason for your choice:					

7. The CBR Tool would help us to store our designs in a consistent manner (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	**6**
Explain the reason for your choice:					

8. How long did it take to input the values for the first case? **5 MINS**

9. How long did it take to input the values for the fifth case? **3 MINS**

Is this time acceptable (Please tick one)? Yes **X** No ☐

If no, please state what you feel an acceptable time is?

10. Are there any other attributes you feel would be useful (Please tick one)? Yes [X] No [ ]

If yes, please state and why? **NEED TO USE THE SYSTEM MORE TO EVALUATE**

11. Use the space below for any further comments?

IS IT POSSIBLE TO INDICATE PRIORITY OF PARAMETERS?

Section 2b: Effectiveness of the recall appropriate past design

1. The appropriate design solution was returned in each case (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	**5**	6
Explain the reason for your choice:					

2. The CBR Tool provides a common understanding of cutting tool design (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	**4**	5	6
Explain the reason for your choice: **NEED TO COMMONISE TERMINOLOGY**					

3. The design reuse viewpoint is useful for sharing information between sales and design (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	**5**	6
Explain the reason for your choice:					

4. The CBR Tool would help us to make informed decisions at the proposal stage (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	**6**
Explain the reason for your choice:					

5. The CBR Tool would help us to make better quotations (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	**6**
Explain the reason for your choice:					

6. Use the space below for any further comments?

Section 2c: Reusing design cases

1. If people involved with these designs had left the company, this information would be invaluable (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	**6**
Explain the reason for your choice:					

2. This information would help me to start the next design (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	**6**
Explain the reason for your choice:					

3. This information is invaluable for a novice to the cutting tool industry (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	5	**6**
Explain the reason for your choice:					

4. This information would be useful for future cutting tool design (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	**5**	6
Explain the reason for your choice:					

5. With the CBR Tool, the design lead time will be reduced in developing new designs (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	**5**	6
Explain the reason for your choice:					

6. Use the space below for any further comments?

NONE

Section 3: Usability (Will the user be able to work the CBR Tool successfully?)

1. How long have you used the CBR Tool (Please tick one)?

Less than 1 hour ☐ Up to 2 hours **X** More than 2 hours ☐

2. Were the instructions on using the CBR Tool made clear (Please circle one)?

Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree
1	2	3	4	**5**	6

Explain the reason for your choice:

3. How easy or difficult was it to use the CBR Tool (Please circle one)?

Very difficult	Difficult	Quite difficult	Quite easy	Easy	Very easy
1	2	3	4	**5**	6
Explain the reason for your choice:					

4. Please rate each of the following (Please circle one for each feature):

a. Navigation within the CBR Tool					
Very difficult	Difficult	Quite difficult	Quite easy	Easy	Very easy
1	2	3	**4**	5	6
Explain the reason for your choice:					

b. Data entry					
Very difficult	Difficult	Quite difficult	Quite easy	Easy	Very easy
1	2	3	4	**5**	6
Explain the reason for your choice:					

c. Cases used			
Not useful	Quite useful	Useful	Very useful
1	2	**3**	4
Explain the reason for your choice:			

d. Ability to understand cases within the CBR Tool					
Very difficult	Difficult	Quite difficult	Quite easy	Easy	Very easy
1	2	3	4	**5**	6
Explain the reason for your choice:					

e. Retrieving design cases					
Very difficult	Difficult	Quite difficult	Quite easy	Easy	Very easy
1	2	3	4	**5**	6
Explain the reason for your choice:					

f. Interpreting similarity values					
Very difficult	Difficult	Quite difficult	Quite easy	Easy	Very easy
1	2	3	**4**	5	6
Explain the reason for your choice:					

5. How could the CBR tool be improved?

AS PREVIOUS COMMENTS PLUS COMPATABILITY WITH ACCESS/EXCEL ETC.

6. What features do you think should be included to the CBR Tool?

ADDITIONAL FIELDS FOR MULTIPLE DIAMETER BORING TOOLS ETC.

7. Please provide any additional comments in the space provided:

NONE