

Cutting Tool Design Knowledge Capture

J. Bailey¹, R. Roy¹, R. Harris² and A Tanner²

¹Department of Enterprise Integration, School of Industrial & Manufacturing Science, Building 53, Cranfield University, Cranfield, Bedford MK43 0AL, UK, j.i.bailey@cranfield.ac.uk, r.roy@cranfield.ac.uk

²Widia Valenite, 12 Alston Drive, Bradwell Abbey, Milton Keynes, MK13 9HA, UK, Richard_Harris@milacron.com, Andrew_Tanner@milacron.com

Abstract: This paper presents the challenges and issues that are encountered when capturing design knowledge in an industrial environment. Identifying and finding a representation for the relevant design knowledge are seen as the key activities in modelling design knowledge. Identification of design knowledge is shown through two case studies undertaken by the first author. In these cases, knowledge is considered to be the difference between the expert and the novice (Knowledge = Expert - Novice). Cutting Tool Design knowledge consists of design, manufacturing, external, internal and technical knowledge and designers consider many of these factors when designing. This paper presents preliminary results of ongoing research carried out at Cranfield University.

1. Introduction

Design in all engineering domains is a complex and knowledge intensive process. At present, most designs are performed by experts using their previous experience. With the demographic change in the labour market, it is becoming increasingly important to capture knowledge in a computer-based system so that it can be reused. In the cutting tool industry there is a shortage of new designers and this problem is worsened as it takes several years for a designer to become knowledgeable about the cutting tool domain. It has been highlighted that current designers come through an extensive apprenticeship, which provides the theoretical and practical knowledge of actually cutting metal. After this stage the designing actually begins. It is difficult for an expert to pass on his/her knowledge to the novice designer and the ongoing research at Cranfield University aims to provide a computer based learning tool or a decision support system to aid both the expert and the novice designer. The paper discusses some issues and initial results in capturing cutting tool design knowledge.

Throughout each stage of the design process the designer can access various items of knowledge and information in order to achieve the final design. Design does not take place in a vacuum; the designer has to consider many aspects in the product design. This paper looks at the information and knowledge needs of the cutting tool designer.

The design of cutting tools is complex and knowledge intensive. In addition to this the market is changing and with the high average age of designers and the lack of recruitment into engineering and, especially the cutting tool industry, results in the loss of this expertise, and according to current Knowledge Management literature this is likely to affect the commercial performance of the company. One answer is to collate and store this information and knowledge in a computer-based system or manual to ensure that the expertise stays within the company. This research is looking into a typical design process of the cutting tool industry in order to establish the information and knowledge used at each stage of the design process. The design process has been modelled using the IDEF₀ modelling technique. It begins with the initiation of the designer 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 can become a case of redesign, modifying an existing design to provide a full manufacturing drawing. This paper aims to identify the types of knowledge and information that the designer requires to complete a design. In the future, the research will move on to capture knowledge from the whole design process in an attempt to develop the decision support system.

2. Models and Methods of Design

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. 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. Design methods can be regarded as any procedures, techniques, aids, or 'tools' for designing [1]. They represent a number of distinct kinds of activities that the designer might use and combine into an overall design process.

2.1 The design models

Design models are the representations of philosophies or strategies proposed to show how design is and may be done [2]. Three classes of models can be seen to emerge – prescriptive, descriptive and computational models.

2.1.1 Prescriptive models of design

Prescriptive models of design are associated with the syntactics 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 [1]. 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 [3, 4, 5].

2.1.2 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 [1]. The original solution goes through a process of analysis, evaluation, refinement (patching and repair) and development [2]. Finger & Dixon [6] 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.

2.1.3 Computational models of design

A computer-based model expresses a method by which a computer may accomplish a specified task [6]. 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 [6] 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 [2].

2.2 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 descriptions of these and 35 other methods can be found in [1, 7].

2.3 Summary

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 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.

3. Design Knowledge Capture

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 [8]. Furthermore, the knowledge is often accumulated over a number of years [9] and that most of the knowledge exists as separate 'islands of knowledge' [3]. 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 [10].

This section presents an overview of the challenges faced while identifying, eliciting, recording and organising the design and manufacturing knowledge. It identifies current practices in the knowledge capture and reuse. It is observed that categorising the type of knowledge and matching a suitable representation for it are the major challenges faced in this area. The knowledge capture requires a good understanding of the design and manufacturing processes, and the development of a detailed process model helps in this understanding.

3.1 Capturing the knowledge

Knowledge capture is the eliciting, recording, and organising of knowledge [11]. The task is extremely difficult to achieve successfully and it requires an understanding of what kinds of knowledge to capture, how to represent it, and how it can be used in the future. The elicitation of knowledge is crucial and has been underestimated in the past [12]. The difficulty arises from identifying the right type of knowledge to achieve the particular functions required by support systems [13] and the knowledge users. Secondly, and probably the most difficult, is the actual elicitation from the domain experts who will have, their own language to categorise the knowledge that is being represented.

A process model of the design has been utilised by the authors to develop an IDEF₀ (Integrated Definition Method) model to understand the functional and structural relationships [14] in the process, and highlight where the designers find information and knowledge. The aim has been to describe in detail each of the inputs, outputs, constraints and resources that go into the design process [15], thus highlighting the categories of information and knowledge which need to be captured and represented.

3.2 Knowledge acquisition

Knowledge acquisition is the process of acquiring knowledge from a human expert (or group of experts) and using this knowledge to build a knowledge based system [16]. Knowledge acquisition and elicitation represents a large amount of the development time in the knowledge capture process. Two types of knowledge may be elicited from the domain expert, explicit and tacit knowledge. Eliciting tacit 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 he or she uses on a day to day basis – it has become second nature to them.

There are various techniques of eliciting the knowledge from the expert, but it is mainly performed by interacting with the expert. These can be broken down into four main areas adapted from [17], shown in Table 1. An example of an indirect

approach (used several times by the author) is to use a case study to show the difficulties faced by a novice in the domain when designing a component. Both the expert and knowledge engineer undertake the same design work from the design brief stage to the final design.

Table 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

This method has highlighted, however, that the novice with basic CAD experience can design the basic component, but without the expert knowledge there are many areas of the component that need further revision, e.g. in a cutting tool design task - the angle at which an insert sits in the shank to achieve a particular cutting condition.

Machine-based knowledge elicitation tools use a computer to elicit and capture knowledge from the designer. There are several systems developed through research [11], such as IDE 1.5 & 2.0, a hypermedia tool incorporating 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 [18]. 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 [10].

A further tool to capture knowledge includes the well-developed KADS (Knowledge Acquisition and Document Structuring) system [17], 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 [19]. This modelling concerns not only expert knowledge but also the various characteristics of how that knowledge is embedded and used in the organisational environment.

XPat [20] 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 IDEF₀ technique. It is primarily a paper based technique allowing representation of tasks graphically therefore avoiding the need for lengthy descriptive text. 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.

3.3 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 [21] using several techniques. These techniques include formal mathematical logic, state-space-speech, semantic nets, production systems and frames & objects [17]. There are four types of knowledge that need to be represented in a computer about a particular domain, declarative knowledge, procedural knowledge, heuristic knowledge and descriptive knowledge. Procedural knowledge refers to how to perform a task, whereas declarative knowledge is factual information and knowing what to do [3].

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'. This 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.

Descriptive knowledge is the formulation of the heuristics used by an expert highlighting concepts in the problem domain which are central to the problem solving process which in effect represent a distilled version of the expert's background knowledge [22]. It provides a description of the problem domain by highlighting the important features and characteristics of the domain.

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 [22]. 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 [23].

Ontologies are content theories about the sorts of objects, properties of objects, and relations between objects that are possible in a specified domain of knowledge [24]. The knowledge representation languages and techniques described are used to represent ontologies. Ontologies facilitate the construction of a domain model providing a vocabulary of terms and relations with which to model the domain [25]. The benefit of using ontologies is the sharing and reuse capability which promotes a shared and common understanding of a domain that can be communicated across people and computers [25]. Noy and Hafner [26] review several prominent ontology design projects comparing purposes of the ontology, its coverage, its size, and the formalism used.

3.4 Summary

This literature survey has identified the processes involved in design and manufacturing knowledge capture. The objective of the knowledge capture is to reuse the knowledge through a computer based system. There is a need to develop a generic framework of knowledge capture for a category of products. The design and manufacturing knowledge need to be represented within one framework so that the designer can have access to manufacturing experience and knowledge and vice versa. Future work will involve the development of a representation technique that can handle both design and manufacturing knowledge. Identification of cutting tool design knowledge is the first stage in the knowledge capture process. The following section describes the first author's indirect approach to knowledge capture illustrated with two case studies.

4. Design Knowledge in an Industry based setting: A Case Study

Metal cutting is a mature 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 toolholding. Metal working know-how and skill can be traced back many centuries. However, metal cutting known in today's industry began with the industrial revolution of the eighteenth and nineteenth centuries and accelerated during the twentieth [27].

Cutting tools range in complexity from the simple single point tools such as turning tools to multi point tools such as milling cutters. The purpose is to remove material from a component or surface to achieve a required geometry e.g. the machining of a casting. For the turning tool shown in Figure 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 is a turning tool which is designed and manufactured to machine an undercut on a cam-shaft. 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.

4.1 Types of knowledge in cutting tool design

In order to capture relevant knowledge of the domain, it has been necessary to design actual cutting tools for customers from the proposal stage through to detail work. This was necessary, as the first author had very limited theoretical knowledge about cutting tool design. He is considered as a typical novice for the domain.

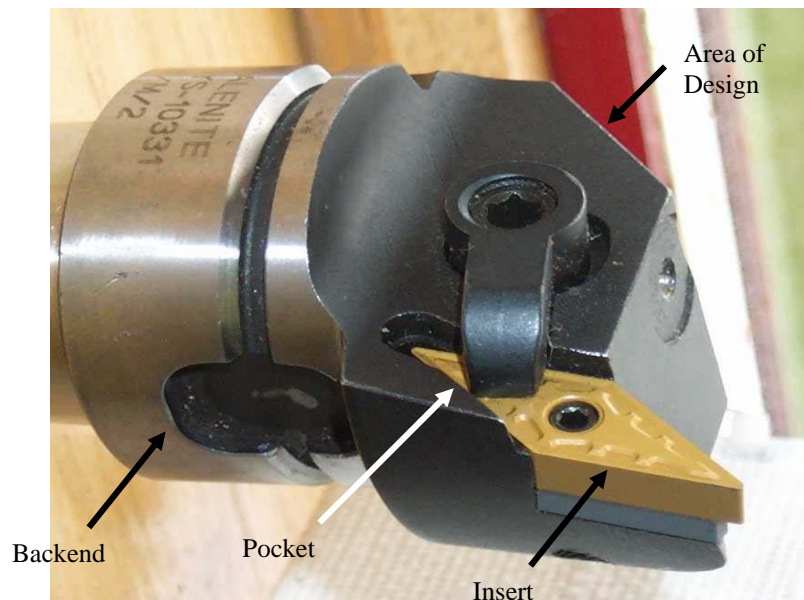


Figure 1: A turning tool.

The purpose of this design work is to understand the principles involved in designing cutting tools and to interact with the experts to identify the types of information and knowledge they utilise throughout the design process, including where they go to find this information and knowledge.

Many cutting tools have been designed by the first author over a period of 5 months, within the organisation, from single point turning tools to more complex milling tools. It has illustrated the difference between the novice designer (the first author), and an expert, who has around 20 years experience designing cutting tools.

The design knowledge is defined as:

$$\text{Knowledge} = \text{Expert} - \text{Novice}$$

This suggests that knowledge within the cutting tool domain is the difference between an expert designing a tool and a novice (the first author). Although it is possible to use textbooks to teach the rudimentary tool design to a novice, there are many instances when specific knowledge of the expert incorporates specialist knowledge of the designed products, which has been gained over the years.

So far only the technical knowledge that is needed when designing a cutting tool has been mentioned. It is certain that a designer would have to have many more types of information and knowledge at their fingertips in order to fully understand the issues that a complete design would have associated with it. Typically, this would involve the customer, economic and supplier knowledge that the designer holds on a personal basis and at a organisational level that has been built up over a number of years. In the cutting tool industry, reuse of past designs is high. Often it will be the designer remembering what they have done before, (see the tool in Figure 1). Here the designer was 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 into account the 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. Knowledge and information types required in cutting tool design are discussed below.

4.1.1 Knowledge in cutting tool design & manufacture

All design has some kind of formal process, in which the designers will follow a set of procedures to produce a final product, a design process. The design process as described within Widia Valenite is shown in Figure 2, which represents one model of design. As with knowledge, getting the designers to articulate this process and make it explicit was found to be difficult as they have been undertaking this process for many years and it has become second nature to them. It was felt important that this process be modelled as to understand the routines that a designer would undertake and also it provided the means to examine how the designers carried out their work.

The process in Figure 2 shows a conceptual stage (proposal) and a description of the technical system which is the checked detailed drawing. This provides a proposal via a salesman which contains information about the cutting conditions, existing tools used in the operation, speeds and feed rates and dimensions of the component to be machined. With this information the designer will produce a proposal drawing, which is then cost estimated. The proposal and estimate are then sent back to the customer for approval from which an approval drawing is sent out,

which returns to be detailed to a full manufacturing specification. After this, the drawing is checked and verified for functionality and manufacturability. If no modification is required then it is sent to contractors for manufacturing. Modifications are made by the detailing engineer which are then checked. At each of these stages the designer uses information and knowledge retrieved from many sources, and in these situations designers spend a lot of valuable design time. It has been observed that knowledge of the manufacturing process is utilised at the proposal stage, as it is here that the designer needs to make sure that the product can be manufactured before the proposal is sent to the customer.

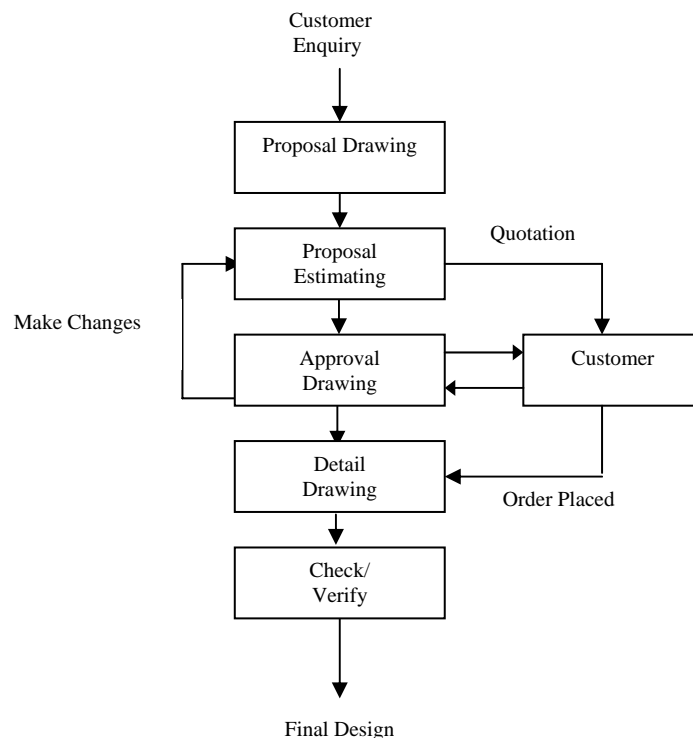


Figure 2: The design process at WIDIA VALENITE [28]

4.1.2 Knowledge in the design

Designers need knowledge and information of past designs, materials, manufacturing information and standards among others to be captured and represented in a computer-based tool. In the process described above the majority of the design work is to modify and reuse past designs. In this situation the designer retrieves only the drawing information from the CAD system without any knowledge of the intent in the design which would describe the decisions undertaken to achieve the design from the customer requirements. Design rationale

is an explanation of how and why an artefact, or some portion of it, is designed the way it is [29] to meet the specifications set out by the customer. Capturing this rationale would be useful as the author has experienced several instances when the designer of a product is unavailable, and it has been too difficult to ascertain as to why the decisions were undertaken to design the product in a particular fashion.

4.1.3 Knowledge in manufacturing

Knowledge in manufacturing differs from that in design. For instance the types of knowledge of interest on the shop floor [30] 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 [30]. What is important to the designer of cutting tools is 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 process the manufacturability of the artefact would be taken into account by the designer. Because of 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 is borne 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 [31].

4.1.4 Non-technical knowledge in cutting tool design

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 the artefact in order to continuously innovate and to keep up with the increasing competition. As described above, not only is the technological knowledge important but also external (outside the organisation) and internal (inside the organisation) knowledge. These types of knowledge are shown in Figure 3 (not exhaustive). A designer needs a basic knowledge of each of the items mentioned in Figure 3. 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.

4.2 Identification of design knowledge

During the design training and observation case study it was possible to identify knowledge of cutting tool design. Most knowledge is implicit and in these cases it is necessary to converse with the experts to find a solution to a specific problem i.e. the location and angle of an insert on a shank.

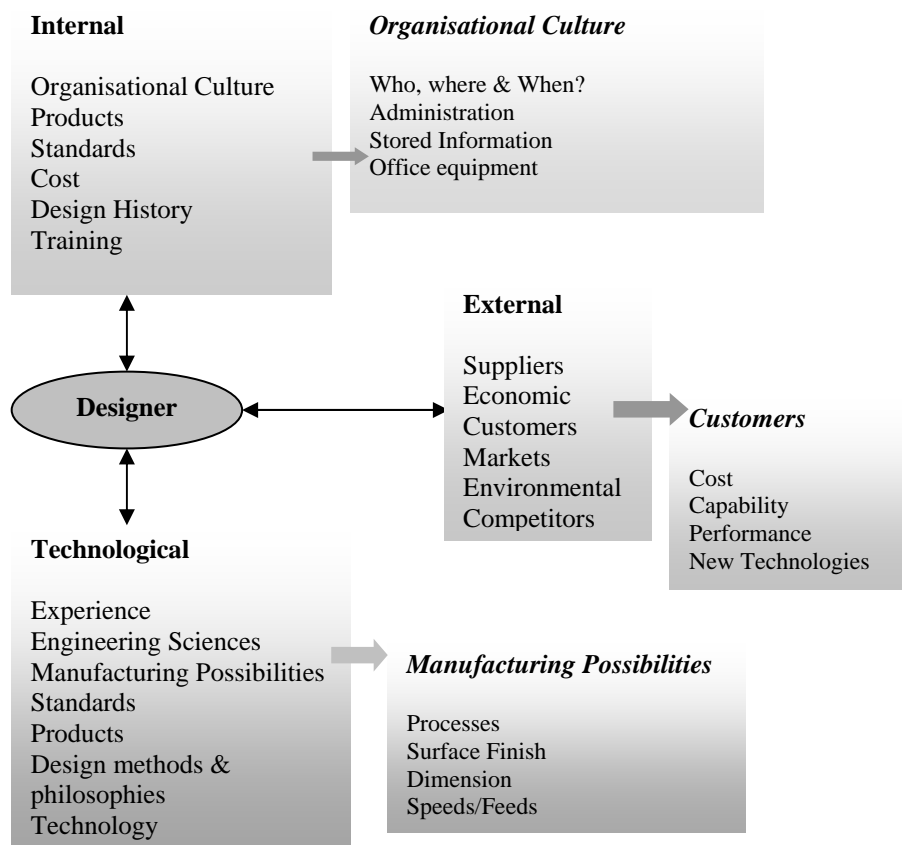


Figure 3: Types of knowledge in cutting tool design.

There are a few examples of explicit knowledge, although poorly documented, which show typical procedures for designing particular types of tool. Examples of design knowledge in this domain include the application of inserts on an end mill shown in Figure 4, and the location of the tooling hole in the placement of the E-Z set unit as shown in Figure 5.

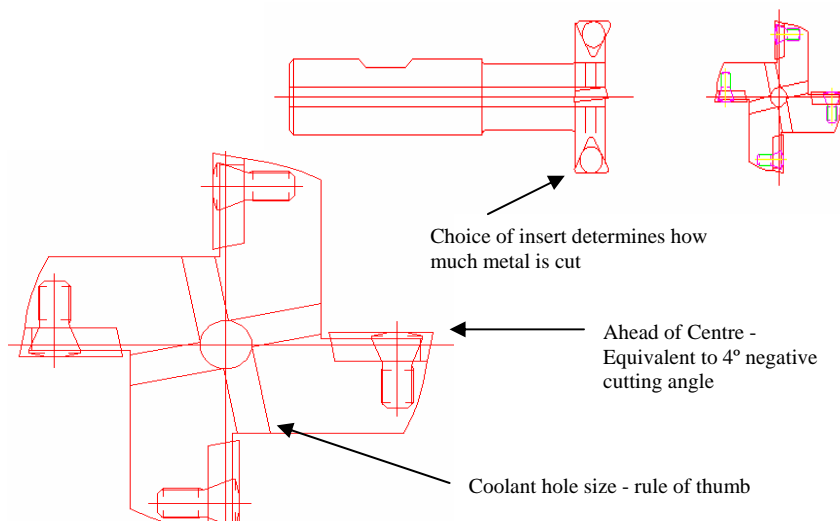


Figure 4: Design of milling cutter.

4.2.1 Case one

The design begins with the sketching of the machined component as shown by the hatched area in Figure 6 from the customer's drawing. Setting of the cutting diameter of 68mm is set, paying attention to 21.50mm cut. With this set, 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.

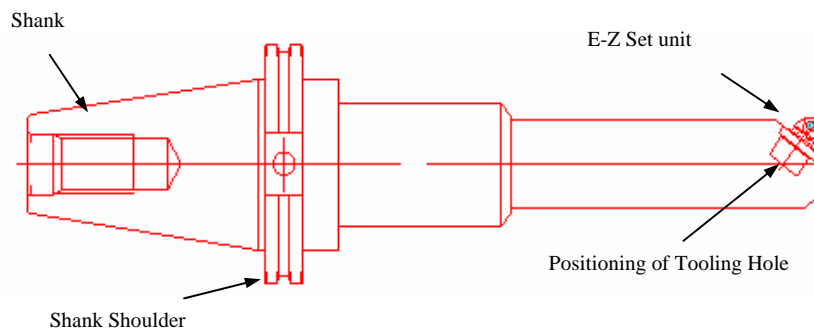


Figure 5: E-Z Set unit.

The questions to arise from the first author when designing this component was the placement of the inserts and the 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.

Designing the end mill for the component shown in Figure 6, required the machining of a 5mm pocket on the backside of the component. The motion of the tool 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.

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 designer (the first 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. 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. The types of knowledge identified in Figure 4 are:

- Placing the insert ahead of the cutting centre line is the equivalent to having 4° negative cutting angle. This information is needed so that it can be machined at 90° to the spindle.
- The size and position of the coolant holes are performed manually/heuristically with the help of the expert relying on his experience of placing coolant holes successfully in previous designs. This ensures the right amount of cooling to contact areas during machining.

The knowledge here is heuristic or a 'rule-of-thumb' and is not written down and can only be accessed by asking the expert the right questions.

4.2.2 Case two

In order to design the cutting tool in Figure 5, product catalogues contain the E-Z Set unit information giving the critical dimensions that are needed in the calculations that are stored 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.

Figure 5 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 E-Z SET unit is the feature of the drawing that contains the insert, and the special feature of this type of unit is the micro adjustment which is achieved through the application of a micrometer gauge contained within the unit. 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 2 which very much depends on the insert corner radius and the diameter of the bar into which the unit is to be placed.

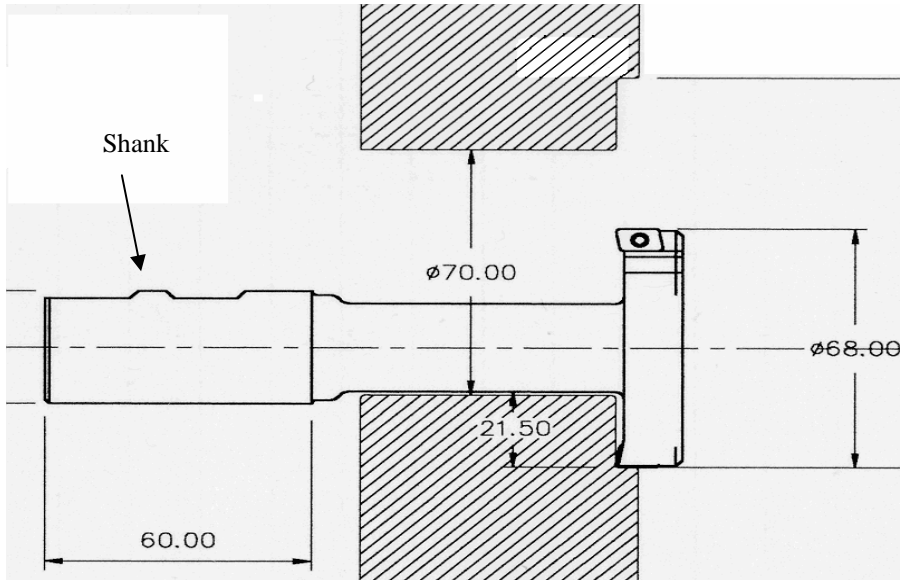


Figure 6: Component to be machined with preliminary design of cutting tool.

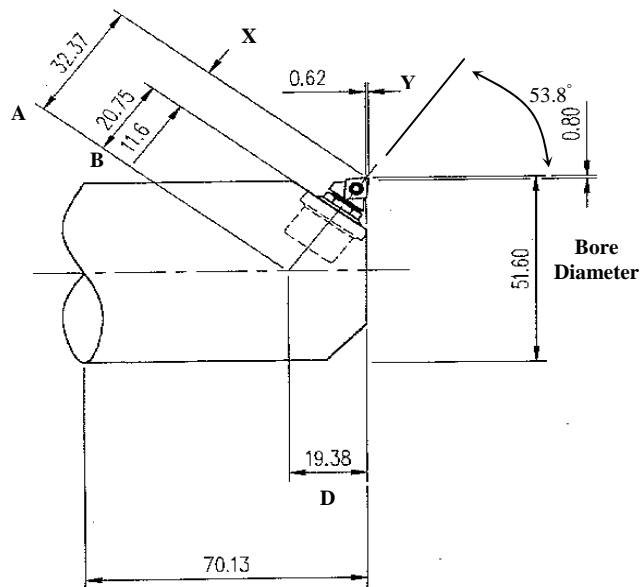


Figure 7: E-Z Set dimensions for calculations.

There is a very small adjustment made to one of the dimensions, as a result of experience, by the experts, and this is not written down. The resulting dimensions

of the calculations are shown in Figure 7. Also, there is a diagrammatic method of achieving the correct front end dimensions of the tooling bar which is written down, but the experience of the expert comes in again, and by intuition they achieve the correct chamfer on the face opposite the E-Z SET unit.

Table 2: Typical E-Z Set calculation

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 Cossec 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".

5. Summary

The paper has outlined the different methods and models of design that have been developed over decades of research. The authors would argue that designers do conform to some features of the models and methods outlined, but in an industry situation such as the cutting tool industry it is not strictly followed. The design process highlighted in Figure 2 is based on the designer's experience of how best to perform the design within the organisation. The authors have also presented the issues that are relevant to capturing knowledge including systems that facilitate knowledge capture. The authors have identified the types of knowledge that are inherent in cutting tool design and have emphasised the need for a global approach to design by considering aspects other than just the technological factors of a design. The case study highlights mainly technical knowledge as this has been experienced first hand. The authors would argue that capturing knowledge about the economy, customer and suppliers as examples would lead to better and informed decisions during design in future years. Hence, it is important to capture design rationales to support the designs. The major challenges in capturing design knowledge and rationale are to organise and categorise the knowledge, and to find a suitable representation to complement it. The types of knowledge identified require a good understanding of the processes involved in the design, and thus it is useful to develop the detail process level model of the cutting tool design process. The research so far has identified cutting tool design knowledge as: Knowledge = Expert - Novice. The knowledge identification is based on an indirect approach, where the first author performed several designs as a novice and identified the knowledge required from experts (this is the difference between an expert and a novice).

6. Future research

The design rationale of the artefact are key to improving decision making and reducing design time. The short life cycle of cutting tool design offers the opportunity to study the whole design process and capture the information and knowledge that leads to successful and non-successful design. The next stage is to capture and represent this knowledge by providing frameworks that are feasible in an industrial environment using further knowledge elicitation techniques. The development of a computer-based interface that can provide support to the computer aided design (CAD) environment to aid the designers in both decision support and training are sought.

Acknowledgements

This is an Engineering Doctorate (EngD) research ongoing at Cranfield University and is supported by EPSRC and Widia Valenite UK. The first author would like to thank the employees of Widia Valenite UK for their help and support when undertaking the case studies.

References

- [1] Cross, N., 1994, *Engineering Design Methods – Strategies for Product Design*, John Wiley & Sons, West Sussex, UK.
- [2] Evbounwan, N. F. O., Sivaloganathan, S., Jebb, A., 1996, *A Survey of Design philosophies, models, methods and systems*, Proceedings of the Institution of Mechanical Engineers, Journal of Engineering Manufacture Part B, vol. 210 B4, pp301-320.
- [3] Hubka, V., Eder, E. W., 1995, *Design Science*, Springer-Verlag, London (UK).
- [4] Hubka, V., 1982, *Principles of Engineering Design*, Butterworth & Co Ltd, UK.
- [5] Hubka, V., Eder, W. E., 1988, *Theory of Technical Systems*, Springer-Verlag, Germany.
- [6] Finger, S., Dixon, J.R., 1989, *A Review of Research in Mechanical Engineering Design. Part 1: Descriptive, Prescriptive, and Computer-Based Models of Design Processes*, Research in Engineering Design, vol. 1, part 1, pp51-67.
- [7] Jones, J. C., 1981, *Design Methods*, Wiley, Chichester, UK.
- [8] Edwards, K., Murdoch, T., 1993, *Modelling Engineering Design Principles*, ICED-93, International Conference on Engineering Design, The Hague, August 17-19.
- [9] Rodgers, P. A., Clarkson, P. J., 1998, *An Investigation and Review of the Knowledge Needs of Designers in SMEs*, The Design Journal, vol. 1, no 3, 1998.
- [10] Brown, D. C., Birmingham, W. P., 1997, *Understanding the Nature of Design*, IEEE Expert, March/April 1997, pp.14-16.
- [11] Gruber, T. R., Russell, D. M., 1991, *Design Knowledge and Design Rationale: A Framework for Representation, Capture, and Use*, Knowledge Systems Laboratory Technical Report KSL 90-45, Stanford University.
- [12] Vergison, E., 1999, *Knowledge Management: a breakthrough or the remake of an old story*, PAKeM 99 - The Second International Conference on The Practical Application of Knowledge Management, 21-23 April 1999, London (UK), pp1-5.
- [13] Khan, T. M., Brown, K., Leitch, R., 1999, *Managing Organisational Memory with a Methodology based on Multiple Domain Models*, PAKeM 99 - The Second International

- Conference on The Practical Application of Knowledge Management, 21-23 April 1999, London (UK), pp57-76.
- [14] Ranky, P. G., 1990, *Manufacturing Database Management and Knowledge Based Expert Systems*, CIMware Ltd, Guildford, Surrey, UK.
 - [15] Macleod, I. A., McGregor, D. R., Hutton, G. H., 1995, *Accessing Information for Engineering Design*, Design Studies, vol 15, no 3, pp 260-269.
 - [16] Smith, P., 1996, *An Introduction to Knowledge Engineering*, International Thomson Computer Press, UK.
 - [17] Winstanley, G (Ed.), 1991, *Artificial Intelligence in Engineering*, John Wiley & Sons, West Sussex (UK).
 - [18] Duffy, A. H. B., 1997, *The "What" and "How" of Learning in Design*, IEEE Expert: Intelligent Systems and their Applications, May/June 1997, pp71-76.
 - [19] Schreiber, G., Akkermans, H., Anjewierden, A. et al., 2000, *Knowledge Engineering and Management: The CommonKADS Methodology*, MIT Press, Cambridge, USA.
 - [20] Adesola, B., Roy, R., Thornton, S., 2000, *Xpat: A tool for Manufacturing Knowledge Elicitation* in Roy, R. (ed.), *Industrial Knowledge Management*, Springer-Verlag, (to appear).
 - [21] James-Gordon, Y., 1992, *Integrating a Knowledge-Based Design System into an Existing Computer Aided Design Environment*, MSc. Thesis, Cranfield University.
 - [22] Davis, R., Shrobe, H., Szolovits, P., 1993, *What is a Knowledge Representation?*, AI Magazine, vol.14, no.1, Spring 1993.
 - [23] Boy G. A., 1991, *Intelligent Assistant Systems in Knowledge Based Systems*, Academic Press Ltd, London (UK), Vol. 6.
 - [24] Chandrasekaran, B., Josephson, J. R., Benjamins, V. R., 1999, *What are Ontologies, and why do we need them?*, IEEE Expert: Intelligent Systems and their Applications, Jan/Feb 1999, pp20-26.
 - [25] Studer, R., Benjamins, V. R., Fensel, D., 1998, *Knowledge Engineering: Principles and methods*, Data & Knowledge Engineering, vol. 25, 1998, pp161-197.
 - [26] Noy, N. F., Hafner, C. D., 1997, *The State of the Art in Ontology Design - A Survey and Comparative Review*, AI Magazine, Vol. 18, No. 3, pp53-74, Fall 1997.
 - [27] Sandvik Coromant, 1994, *Modern Metal Cutting – A Practical Handbook*, Sandvik Coromant Technical Editorial Department, 1994.
 - [28] Bailey, J. I., Roy, R., Harris, R., Tanner, A., *Knowledge in Design and Manufacturing*, NCMR 99, 15th National Conference on Manufacturing Research, 6-8th September 1999, Bath, UK.
 - [29] Gruber, T., Baudin, C., Boose, J., & Weber, J., 1991, *Design Rationale Capture as Knowledge Acquisition Tradeoffs in the Design of Interactive Tools* in Birnbaum, L., and Collins, G. (eds), *Machine Learning: Proceedings of the Eighth International Workshop*, San Mateo, CA: Morgan Kaufmann, pp.3-12.
 - [30] Ravindranathan M, Khan T. M., 1999, *A Methodology for Structuring Shop Floor Knowledge*, PAKeM 99 - The Second International Conference on The Practical Application of Knowledge Management, 21-23 April 1999, London (UK), pp83-91.
 - [31] Roy R., Williams G., 1999, *Capturing the Assembly Process Planning Rationale within an Aerospace Industry*, ISATP '99, July 21-24, Porto, Portugal.