A manufacturing model to enable knowledge maintenance in decision support systems

A Manufacturing Model to Enable Knowledge Maintenance in decision Support Systems

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DEDICATION

This thesis is dedicated to:

My beloved wife Claudia and son David Alejandro, without whose moral support this work would not have been completed. Your presence in my life has enabled me to achieve all that I have. With all my love to them.

To my parents who taught me the merit of education and for the generous love they gave me throughout my life.

To my parents-in-law for their love, encouragement and support.

To my relatives because they are important in my life.

To God, thank you for everything YOU always give me.

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ABSTRACT

The product development process, within a typical manufacturing company, utilises huge amounts of knowledge related to manufacturing and design activities. Knowledge based systems are increasingly being used to support manufacturing and design decisions. These systems are important tools for obtaining a competitive advantage and leverage using company "know-how". However, it is important to define suitable knowledge structures in the creation of these decision support systems. Due to the significant volume of knowledge generated in the manufacturing and design stage, there is a need to create structures and methods that readily manage and maintain the knowledge in order to a) assure the long-term use of these systems b) improve the company's competitiveness.

The research reported in this thesis explores and defines a Manufacturing Facility Information and Knowledge Model (MFIKM) allowing a) the ability to store and manage various types of knowledge, b) the capturing of valuable new knowledge using a knowledge maintenance method. The understanding of an information and knowledge infrastructure using different types of knowledge categorisation has been explored. The major emphasis has been placed on understanding the facility knowledge structure related to processes and resources supporting process planning decisions. Using a knowledge maintenance life cycle as a method to maintain knowledge, it was possible to capture new and valuable machining knowledge using different types of representations. Knowledge models and methods are essential in the definition of structures to support manufacturing decisions allowing knowledge management and maintenance.

It has been shown that the knowledge structures defined for the new model can serve as a source and repository for different types of knowledge allowing the support of manufacturing decisions with up-to-date knowledge. The framework defined enables the structuring of facility knowledge, processes, and resources, as super classes; improving the understanding of the relationships and dependencies among them, and allowing accessibility depending on the characteristics of each. A UML tool helped in the creation of new structures detailing attributes for the classes defined. An experimental system has been implemented using the object-oriented database ObjectStore© and the Visual C++ programming environment. The MFIKM has been explored using scenarios from machining knowledge to successfully demonstrate the feasibility of knowledge maintenance supporting process planning decisions using the knowledge structures defined.

GLOSARY OF TERMS

AI – Artificial Intelligence

CBR – Case Based Reasoning

DFM – Design for Manufacture

DM – Data Mining

ICAM – Integrated Computer Aided Manufacturing

IDEF – Integration Definition for Function

ISO –International Organization for Standardization

KBE – Knowledge Based Engineering

KBS – Knowledge Based Systems

KDD – Knowledge Discovery in Databases

KM- Knowledge Management

MFIKM – Manufacturing Facility Information and Knowledge Model

MIM – Manufacturing Information Modelling

MM- Manufacturing Model

OEM – Original Equipment Manufactures

OO – Object Oriented

OOP – Object Oriented Programming

PM – Product Model

STEP – Standard for the Transfer and Exchange of Product Model Data

UML – Unified Modelling Language

XML – eXtensible Markup Language

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CHAPTER 1

1. INTRODUCTION

1.1. Context

Manufacturing companies utilise large amounts of knowledge to produce products. These companies apply manufacturing knowledge to develop products according to customer requirements and competitive prices. Over time, the combination of new technologies, product innovation and worker's experience have improved the manufacturing knowledge used to produce products and, as a consequence, this knowledge has expanded. Therefore an important aim in manufacturing companies is to retain, transfer and improve manufacturing knowledge.

The understanding of different types of knowledge is important in the creation of manufacturing knowledge structures and has become a key issue in the knowledge maintenance of 'know-how based' applications systems. Even though different systems and computational tools are used to support design and manufacturing decisions, there is a need for integration between the current knowledge that these systems use and the new knowledge creation process. Continuous improvement in manufacturing companies often produces a large expansion of manufacturing knowledge, as a consequence, employees continue using particular techniques to retain, transfer and reuse knowledge. Under these circumstances, it is difficult to obtain a competitive advantage levering what the company "knows" due to the key knowledge lost. Therefore to understand types of knowledge and to explore new knowledge structures to readily access and maintain manufacturing knowledge is useful in 'know-how based' applications systems.

In recent years Knowledge Based Systems (KBS) have been used in the product development process to support manufacturing and design decisions. These systems utilise large amounts of knowledge related to manufacturing and design activities. As a result, due to the substantial volume of knowledge generated in the manufacturing and design stages, there is a need for a new approach to structure, that enables the knowledge to be readily maintained, assuring the long-term use of these systems (Rezayat 2000), (Young 2003).

The concept of information models is an accepted manner of information integration and is recognised as an area of research where effective results can have wide-ranging implications for improving the decision-making process. Significant advances have been made in Manufacturing Information Modeling (MIM) to support decisions throughout the product development process using the concepts of: (a) the Product Model, which captures product characteristics; and (b) the Manufacturing Model, which stores manufacturing information. Even though these models are mainly focused on support of the decision making process, the need to develop flexible systems that can be readily maintained with up-to-date information still exists. Many industrial and research groups have developed the concept of the Manufacturing Model as a tool for managing manufacturing information biased towards the practical requirements of each group. Existing implementations of manufacturing models allow access to information to support decision-making. However, they did not provide an efficient means for maintaining the information database.

The majority of existing methods for maintaining manufacturing knowledge have one or more of the following shortcomings: (a) the inability to deal with various types of knowledge; (b) the huge time and effort required to constantly update knowledge; (c) the capture of new and valuable knowledge.

The work reported in this thesis contributes to the area of information and knowledge structure to support manufacturing decisions. The structures of the manufacturing model have been defined to achieve a suitable access to, and maintenance of, the manufacturing knowledge. The interaction of the manufacturing data model proposed shows a specific interaction with the product data model in order to identify the product characteristic that needs to be produced. Emphasis has been placed on investigating a suitable manufacturing model structure in order to readily access and maintain updated manufacturing knowledge.

1.2. Aims and Objectives

The aim of this research is to explore and investigate Manufacturing Knowledge Maintenance by creating (a) new manufacturing knowledge structures that enable improved access to different types of manufacturing knowledge; and (b) a novel manufacturing knowledge maintenance method to support the maintenance of manufacturing knowledge.

In achieving this aim, the major objectives of the research can be stated as follow:

I. To understand the different types of manufacturing knowledge and their representation.

II. To define manufacturing model structures that enables the storage of the different types of manufacturing knowledge.

III. To explore methods to support the maintenance of manufacturing knowledge.

IV. To build an experimental software tool which will give access to and maintenance of manufacturing knowledge.

V. To evaluate the results achieved by the experimental software tool.

1.3. Scope

This research is written in the context of information and knowledge modelling for manufacture. The research explores manufacturing knowledge and how it can be structured in such a manner that it can be maintained and updated.

Manufacturing knowledge is very wide and this research doesn't deal with the whole range of manufacturing knowledge. Hence machining knowledge has been targeted as manufacturing knowledge with strong emphasis being given to manufacturing knowledge for making holes. The hole manufacture knowledge was initially used to explore the kind of structures that are important in this research and was used to help the construction of an experimental system in order to test the research ideas. It is important to emphasise that hole manufacture knowledge is simply an example used to explore which parts of the structures are important. However, the approach can be extended beyond the manufacture of holes.

There are different decision support systems based on manufacturing knowledge. However the most generally applicable area for manufacturing knowledge in terms of making decisions about how to make things is process planning. Process planning has therefore been used in order to explore the use of the MFIKM. An experimental software application has been applied to validate the research ideas using process planning as example.

1.4. Research environment

This section presents the research environment in which this work was carried out, and provides the main arguments related to the tools used to evaluate the concepts of the research work.

The research presented in this thesis is a continuation of a Manufacturing Information Model (MIM) research project, where a Product Model (PM) and a Manufacturing Model (MM) were considered as information repositories. A PM has structure that provides a source and repository for information concerning a product under development, in comparison a MM is a similar concept but represents the capability of a manufacturing facility. A KBS was developed from various components with the ability to share information between a PM and a MM supporting machining-related activities. However, the need of new models to structure the manufacturing knowledge was recognised (Zhao et al. 2000)

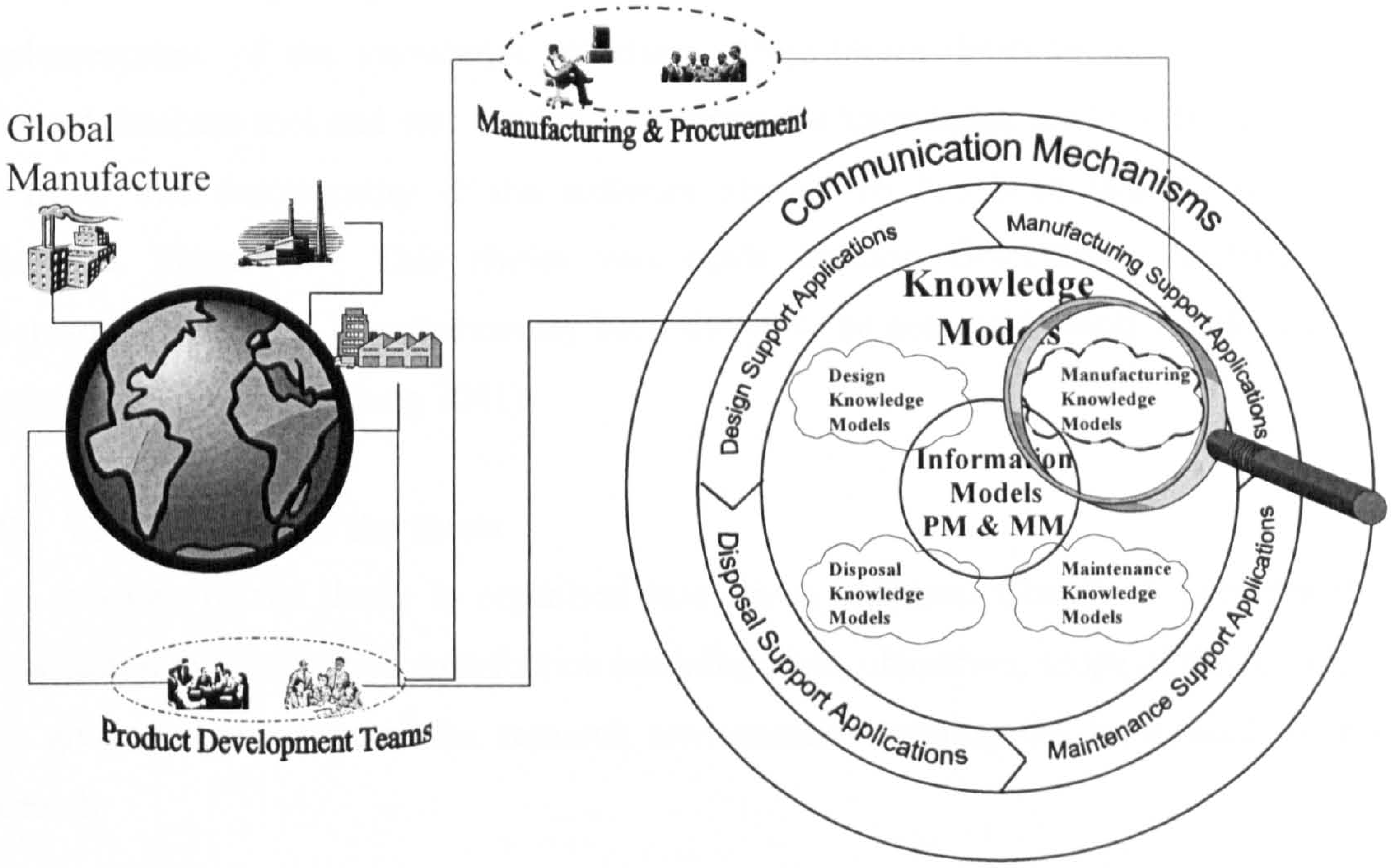


Figure 1-1 Manufacturing knowledge models (Young et al. 2000).

Figure 1-1 depicts an information and knowledge framework with the premise that computational systems in integrated design and manufacture can provide support to engineers by offering them quality information on which to base their decisions. The research presented in this thesis focuses on manufacturing knowledge models to support knowledge maintenance in KBS. The research area is depicted in Figure 1-1 using a magnifier.

The Unified Modelling Language (UML) was used as a vehicle for the object oriented design and analysis of the manufacturing information and knowledge structures by obtaining a set of class diagrams, describing the relationships between classes in the MFIKM. This choice was made because UML has become recognised as an accepted language to support the design and modelling of multiple perspectives of information systems (Costa and Young 2001). The author of this thesis found that object oriented structures allow good representation of processes and resources knowledge at different levels of detail. Appendix A of this thesis contains an explanation of the Unified Modelling Language (UML) as a tool to design and analyse the knowledge structures proposed. The next paragraphs discuss additional issues related to the object oriented programming tools used in this research.

UML was used to define the information and knowledge structures of the MFIKM through a class diagram representation. Then an object-oriented database was used to store and access the large amount of information and knowledge that exists in the implementation of the knowledge structures. ObjectStore database is a pure object oriented database tool and was used to implement the knowledge model schemas of the MFIKM. The functionality of the software application has been realised by using Microsoft Visual C++ This choice was made because ObjectStore database and Microsoft Visual C++ have previously been shown to be acceptable tools in information modelling (Costa and Young 2001)

1.5. The structure of the thesis

The structure of the thesis is organised into seven chapters. Chapter 1 provides the introduction to the research contribution outlining aims, objectives, scope of the research, and gives a description of the research environment defining the tools used in this research.

Chapter 2 presents a literature review of relevant areas of related work. It starts with the main issues that must be considered in knowledge management, moves to a survey of decision support systems based on knowledge and finally provides information and knowledge modelling issues.

Chapter 3 highlights the research novelty contribution of the work in the context of the problem area that the research has addressed. This chapter also bases the contents of chapter 4 and 5 that provide the definition and relationships about the structures for the MFIKM.

Chapter 4 describes the process followed to describe the information and knowledge structures in the MFIKM.

Chapter 5 explains the information and knowledge interactions taking place in the MFIKM.

Chapter 6 presents the implementation of the experiments conducted to explore the access and storage of different types of manufacturing knowledge into the MFIKM providing process planning support decisions with up-to-date knowledge.

Finally, chapter 7 presents the discussion of the major issues explored in this thesis, as well as the conclusions and the recommendation for further developments in this area.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Introduction

This chapter presents the main topics currently researched and related to the main theme of this thesis.

Three main sections are reported in this chapter. The first section describes an overview of the emerging topic of Knowledge Management (KM) and the importance of knowledge type definitions. The second section reviews research on decision support systems based on knowledge. The third section presents the main aspects and previous research on information and knowledge modelling.

The review realised in this chapter identifies the gap between the proposed research and previous work and provides the justification for this research, highlighted in the next chapter.

2.2. Knowledge management

2.2.1. General issues

An important aim in human history has been to retain, transfer and improve knowledge. A company is powerful if it has the ability to take advantage of all the available knowledge and have the capability to apply this knowledge to human requirements. In this case, manufacturing companies have different systems of using knowledge to design and manufacture products. Nowadays, globalisation of the manufacturing industry and the worldwide competitive economy is forcing industrial leaders in the manufacturing and service sector to fully utilise the knowledge available. Through time, technologies have improved the knowledge used to develop products and, as a consequence, this knowledge has expanded. Under these circumstances, to improve product development decisions and to obtain a competitive advantage, industry must effectively retain, transfer and improve the knowledge (Beckett 2001).

Lee and Yang (Lee and Yang 2000) noted that information is becoming ever more important in our economy, and most corporations see that knowledge can confer competitive advantage. But corporations are already flooded with information, and most of us have more of it than we can handle. Knowledge management (KM) tries to resolve the troublesome paradox.

In recent years the term KM has been an emerging topic that has commanded attention and support within academics and industry (Meso and Smith 2000). There has been a lot of research into knowledge management to effectively structure, retain, transfer and improve company's knowledge. KM definitions are presented in the next paragraphs.

KM is the combination of operational principles, organisational structures, and technologies that help knowledge employees leverage their creativity and ability to deliver business value. This new concept has as its focus the creation, dissemination and leveraging of knowledge to fulfil organisational objectives (Lee and Yang 2000).

KM is a mechanism that facilitates critical organisational processes to support: a) innovation, the generation of new ideas, and the exploitation of the organisation's thinking power; b) capturing insight and experience; c) the reuse sources of know-how and expertise, d) fostering collaboration, knowledge sharing, continual learning; e) improving the quality of decision making (Levett and Guenov 2000).

KM is the process of capturing the collective expertise and intelligence in an organization and using them to promote innovation through continued organizational learning (Brand 1998). Carneiro (Carneiro 2000) reported that knowledge management is a manner to influence innovation and competitiveness in an industry. He pointed out the importance of knowledge development and the role of knowledge management in order to assure competitiveness. He emphasised that it is important to identify the types of knowledge that best fit innovative efforts and competitive strategies.

KM is the process or practise of creating, acquiring, capturing sharing and using knowledge and depends upon effective human interactions (Wickert and Herschel 2001). For this reason knowledge based companies critically depend on the contribution of their employees (Kautz and Thaysen 2001). Under this circumstance, it is important to create KM tools to maximise the knowledge use.

Some researchers have explored different methodologies to implement the KM. Meso and Smith (Meso and Smith 2000) defined an organizational knowledge management system that provides the creation of new knowledge, the assembly of externally created knowledge, the use of existing knowledge, and the finding of knowledge from internal and external sources. Rubenstein et al. (Rubenstein-Montano et al. 2001) found that developing a KM methodology is a critical step for organisations that are serious about conducting KM activities. However, these researchers agreed that additional understanding in different types of knowledge is needed.

It can be observed according to the explanations above that knowledge is an important subject in organisations and how to organise the information and knowledge is an important issue. KM is focused on the research of new methods and tools to understand the knowledge within a company providing competitive advantage. However, the research presented in this thesis is focused on manufacturing knowledge management exploring methods and tools to support process planning decisions with updated knowledge.

The innovation, knowledge creation, knowledge discovery and knowledge workers have been strongly related with the KM subject. In the next paragraphs some examples are presented.

Effective KM applications have positive effects for innovation. 3 M has employed KM systems focussing in tacit knowledge transfer finding important applications of new ideas into practical products and services (Brand 1998). The success of an innovative product is connected with the knowledge creation and knowledge that people have to solve a problem (Carneiro 2000). Academics and industry are currently showing a significant interest in understanding the KM models and the role of classification of knowledge for organisational innovation based on codified knowledge (Sørensen and Lundh-Snis 2001), (Jang et al. 2002). The ability to create a stream of revolutionary new products can represent a sustainable competitive advantage for firms in almost any industry and tacit knowledge possessed by individuals can provide breakthrough innovations (Mascitelli 2000), (Perez-Bustamante 1999).

Knowledge creation, utilization and the management of knowledge are at the core of the new product development process and are becoming the primary source of sustainable competitive advantage in an era characterised by short product life cycles, dynamic markets and complex processes (Ramesh and Tiwana 1999). This is a reason why it is important to move towards the definition and understanding of types of knowledge in the role of information systems in managing knowledge (Gao et al. 2003). The development of systems to assist in managing knowledge has been a topic of considerable interest and to capture, reuse, maintain and transfer knowledge are essential elements of such systems (Prasad 2000), (Jurgens 2000).

Through time different researchers have studied manners in which knowledge is created and exploited. The new knowledge generated from the conversion of different types of knowledge is the result of continuous innovation. The effectiveness of the conversion depends on organisational structures and leadership styles (Nonaka and Takeuchi 1995). The importance of knowledge will revolve around knowledge creation and the radical innovation that this can release. Knowledge created from a strategic intent to position an organisation for successful long term success, will need to be leveraged to get the most benefit from it (Sharkie 2003).

Knowledge creation is an important part in the KM because it is an important resource that can lead to sustained increase in profits. Knowledge creation is a continuous process whereby individuals and groups within firm and between firms share different types of knowledge. However it is important to align the knowledge models, the knowledge strategies and the knowledge creation in the organisations (Choi and Lee 2002).

A purpose of KM is to integrate the internal and external knowledge that employees apply to solve existing problems as well as to innovate business expansion (Hong and Kuo 1999). People who have expertise to solve a problem i.e. designers, operators, technicians, etc., have always passed the knowledge on to future generations by telling stories about their thoughts and experiences (Malhotra 2000). The knowledge worker refers to the employees who possess competences, knowledge and skills in the organisation. These people participate actively in the innovation and creativity process in organisations. If a person leaves the organisation, their knowledge goes with them. For this reason it is important to create methods to organise the knowledge to encourage the open sharing and use of all forms of knowledge (Smith 2001).

According to these last definitions it can be observed that innovation, knowledge creation, knowledge discovery and knowledge workers are strongly related with the KM. However it is important to clarify differences between information and different types of knowledge involved in the organisations. In the next sections these concepts are presented.

2.2.2. Data, information and knowledge

Knowledge is a complex and multifaceted concept and as previously discussed, different authors have studied the knowledge in KM, however they found relevant differences between data, information and knowledge that are explained in the next paragraphs using different examples connected between them. Figure 2-1 depicts these differences.

"Data relates simply to words or numbers the meaning of which may vary and is dependent upon the context in which the data is used" (Harding 1996). Data are simply symbols with no context and no relationships. For example, the numbers completely out of context 500 or 10% are just pieces of data (Bellinger G. et al. 2003). On the other hand, the separate characters: "5", "cm", "A" and "B" are additional data examples. In addition, in the product realisation process, data is just the numbers and symbols used in describing a line, a vertex, the material used, the machine capacity, etc, (Mills and Goossenaerts 2001).

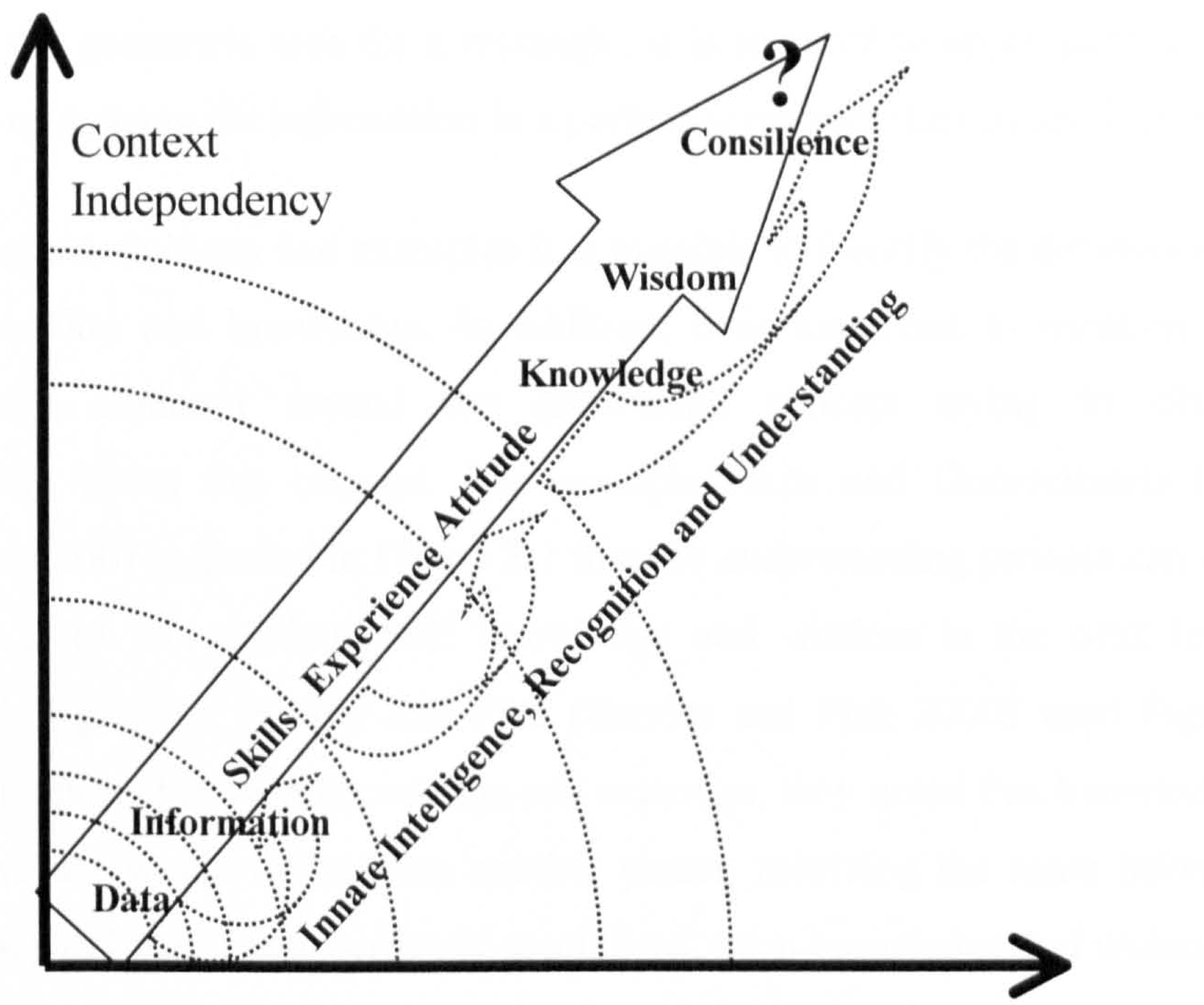


Figure 2-1 Data, information and knowledge representation (Mills and Goossenaerts 2001).

"Information is data, which is structured or titled in some way so that it has a particular meaning" (Harding 1996). Information is processed data and structured to provide a meaning within a given context. Information exists when data relationships are recognised within a specific context. The principal and interest rate become meaningful in a bank savings account context. £500 as principal in the amount of money and 10 % as interest rate make a meaning in the savings account (Bellinger G. et al. 2003). In geometry context "5 cm. from A" and "5 cm. from B", most people would understand these relationships as a distance from the locations "A" and "B". Symbols written in this way, impart meaning to the reader (Mills and Goossenaerts 2001).

Knowledge is much more difficult to define because it has so many possible interpretations. "Knowledge is information with added detail relating to how it may be used or applied" (Harding 1996). Knowledge is the appropriate collection of information and the sum of what is known, in other words is the body of truth using information and principles acquired by mankind (Mills and Goossenaerts 2001). £500 as principal in a savings account and 10% interest yearly, at the end of one year a bank will compute the interest of £50 over the principal, as a consequence the total amount in a year is £550 (Principal + interest yearly) (Bellinger G. et al. 2003). Considering a four-sided figure with 5 cm by side, by geometry is well known that the area is 25 cm^2 (area = A X B). These are knowledge examples where to get the answers of the total amount of savings in a year and the geometric area for a rectangle, it is required to apply particular piece of knowledge organising the information in a particular manner (Lovett and Bancroft 2000).

Through these definitions and examples it is possible to identify the differences between data, information and knowledge. In addition, it is important to mention that some authors have explored around the knowledge concept trying to obtain more understanding about this concept. For example Mills and Goossenaerts (Mills and Goossenaerts 2001) reported in Figure 2-1 that the understanding process can create new knowledge from the previous held knowledge and wisdom is the next level of the understanding process. Bender and Fish (Bender and Fish 2000) used Figure 2-2 to explain differences between knowledge and expertise, they noted that knowledge formed by an individual would differ from another person receiving the same information. In addition, they defined that expertise is specialised, deep knowledge and understanding in a certain field, which is far above average. Any individual with expertise is able to create uniquely new knowledge and solutions in his/her field of expertise. In this sense, expertise is gained through experience, training and education and it is built up from scratch over a long period of time by an individual and importantly remains with that person.

The understanding, wisdom and expertise definitions are important concepts to comprehend knowledge transformation (Bender and Fish 2000). However, understanding of data, information and knowledge differences is important to knowledge management (Mills and Goossenaerts 2001). Data, information, knowledge, understanding, wisdom and expertise concepts are important in this work because they are applied in the process of creating, acquiring, capturing, sharing and using manufacturing knowledge though the knowledge structure.

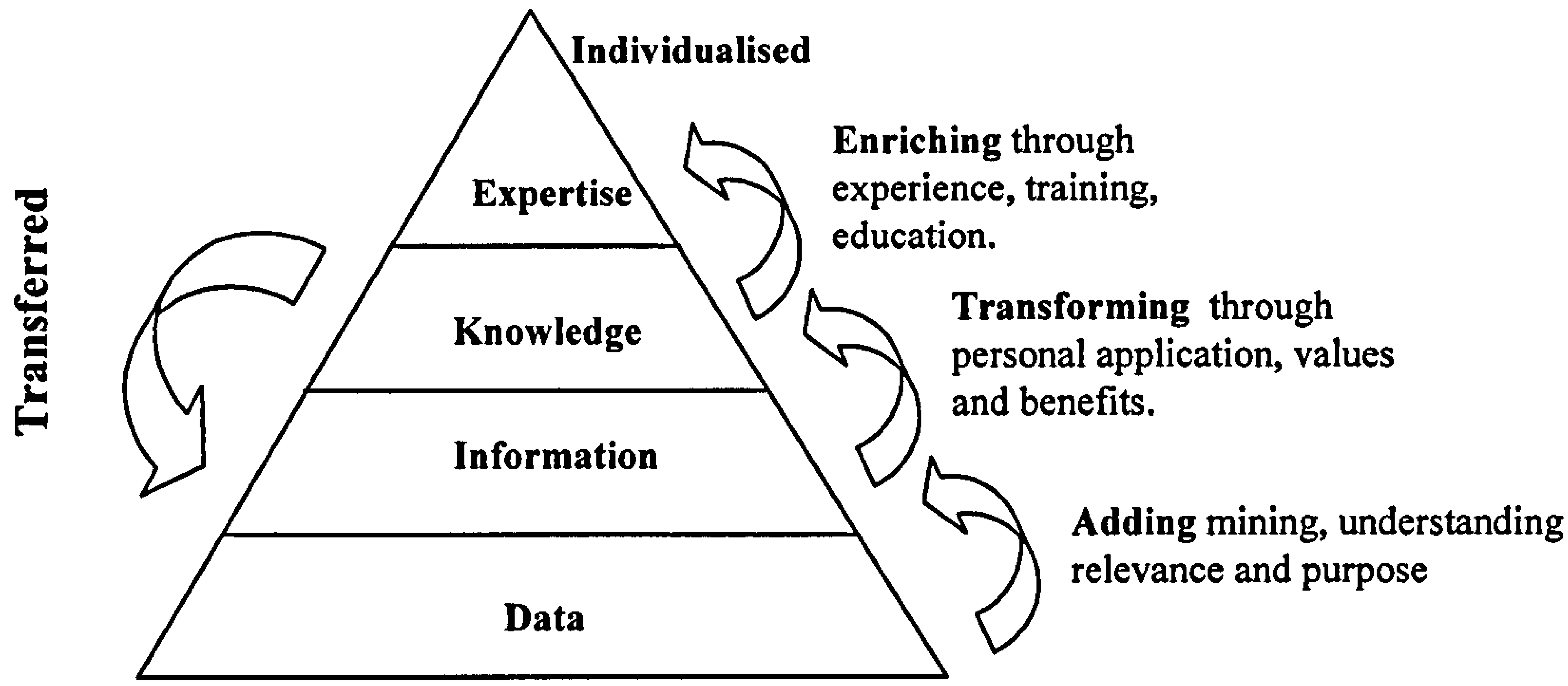


Figure 2-2 Knowledge hierarchy (Bender and Fish 2000)

2.2.3. Knowledge types

2.2.3.1 General issues

There are many kinds of knowledge at different levels and areas in organisations. It is important to explore the understanding of the different types of knowledge within organisations related to: technical competencies and capabilities, organisation capabilities and "system" capabilities in terms of interactive links (Beckett 2001). However, different types of manufacturing knowledge used in the product manufacture are explored according to the research scope presented in this thesis. This is a reason why knowledge types are discussed in this section clarifying key differences between them.

Manufacturing is a knowledge intensive process and uses large amounts of types of knowledge. The clarification of the knowledge types is essential for the success of concurrent engineering, new information technologies, and future KBS. An important requisite for knowledge usage is adequate knowledge structure definitions, describing the role of each knowledge type in the overall context. The lack of understanding related to the different kind of knowledge taking part in the functionality of the decision support systems based on manufacturing knowledge is a significant shortcoming (Klein R. 1998). Working in this line Yoshioka et al. (Yoshioka et al. 1998) suggested a knowledge sharing mechanism among agents based on a common ontology to collect knowledge. The research presented in this thesis is focused on manufacturing knowledge exploring suitable knowledge structures to understand and apply different types of knowledge.

2.2.3.2 *Explicit Knowledge*

Several researchers have studied the different types of knowledge that humans use to make decisions (Markus 2001). Explicit knowledge consists of formal policies and procedures (Nonaka and Takeuchi 1995). Explicit knowledge is a formal and systematic type of knowledge consisting of basic facts and storable document sets (Nickols 2000). Explicit knowledge, as the first word implies, is knowledge that has been articulated and very often captured in the form of text, tables, diagrams, product specifications and so on (Mahe and Rieu 1998). The explicit knowledge corresponds to formalised knowledge with a known syntax and a known semantics. This type of knowledge transfer is relatively easy, without knowledge lost (Zheng et al. 2001). Explicit knowledge is not too difficult to identify and structure and the majority of the current decision support systems based on knowledge use explicit knowledge (Chung et al. 2003). It has been decided to use data and information organised in formats such as graphs, tables and procedures to capture and organise explicit knowledge to explore knowledge maintenance ideas as the possibility to by used to drive software tools. The reason is because; explicit knowledge representations can provide good support to knowledge maintenance.

Examples of explicit knowledge are a) the formula for finding the area of a rectangle (i.e., length times width); b) documented best practices; and c) the formalised standards by which an insurance claim is adjudicated. In order to support decisions this type of knowledge is commonly organised in formats such as graphs, tables and procedures. Chapter 4 presents some manufacturing explicit knowledge examples according to the above definitions and discussion.

2.2.3.3 *Tacit Knowledge*

An important capability for competition is the understanding and management of knowledge as intangible asset (Beckett 2001). Tacit knowledge consists of personal relationships, practical experience and shared values (Nonaka and Takeuchi 1995). Tacit knowledge is a complex and crucial type of knowledge difficult to manage in modern organisations (Balconi 2002). This is a reason why there is still much to learn about tacit knowledge management (Augier and Vendeleo 1999). Tacit knowledge constitutes the major part of what we know and it is difficult for organisations to fully benefit from this valuable asset (Hackley 1999). Some authors agree that tacit knowledge needs to be managed in tacit ways and must be manageable and separated from the employees, so that the knowledge resources do not go home at night (Stenmark 2000). There has been some interest in management of tacit knowledge but the field is still relatively unexplored and not fully understood (Kreiner 2002). A deeper understanding of externalisation and diffusion of tacit knowledge must be obtained for an organisation to unleash the resources of tacit knowledge. To rely on personal tacit knowledge is risky (Cheah and Abidi 2001). Conversion of tacit knowledge to explicit or at least ability to share it offers greater value to an organisation (Haldin-Herrgard 2000).

Most of the authors agree that tacit knowledge is very difficult to articulate based on the idea that persons know more than they can say (Nonaka and Takeuchi 1995). Tacit knowledge corresponds to non-formalised knowledge including cognitive elements, diagrams, beliefs and mental models (Ackerman et al. 2003). This type of knowledge corresponds to personal experience, instinctive ability, and other skills that are difficult to structure (Nickols 2000). Tacit knowledge plays a substantial role in decision making for the product realisation process because it is the sum of a person's experience and training, as a consequence it is difficult to provide information technology support for it (Mills and Goossenaerts 2001), (Zheng et al. 2001). Tacit knowledge is the context of innovation and the breakthrough innovations result from the harnessing of tacit knowledge possessed by individual and project teams (Mascitelli 2000).

2.2.3.4 Implicit Knowledge

Implicit knowledge is the type of knowledge that can be articulated but has not (Nickols 2000). Implicit knowledge has a bridge property that links together the explicit and tacit components. In other words, implicit knowledge is a type of knowledge considered as a link between explicit and tacit used as a link in a knowledge management system (Zheng et al. 2001). Figure 2-3 shows the relationships between explicit, tacit and implicit knowledge using an executable knowledge model. Implicit knowledge is the kind of knowledge that has its existence implied by or inferred from observable behaviour or performance (Nickols 2000). For example a pilot can learn from an Olympic diver the twists, tumbles and pikes. The pilot can try to perform afterwards the movements of the diver using his airplane (Zheng et al. 2001). Workers can discover new knowledge studying and analysing similar processes.

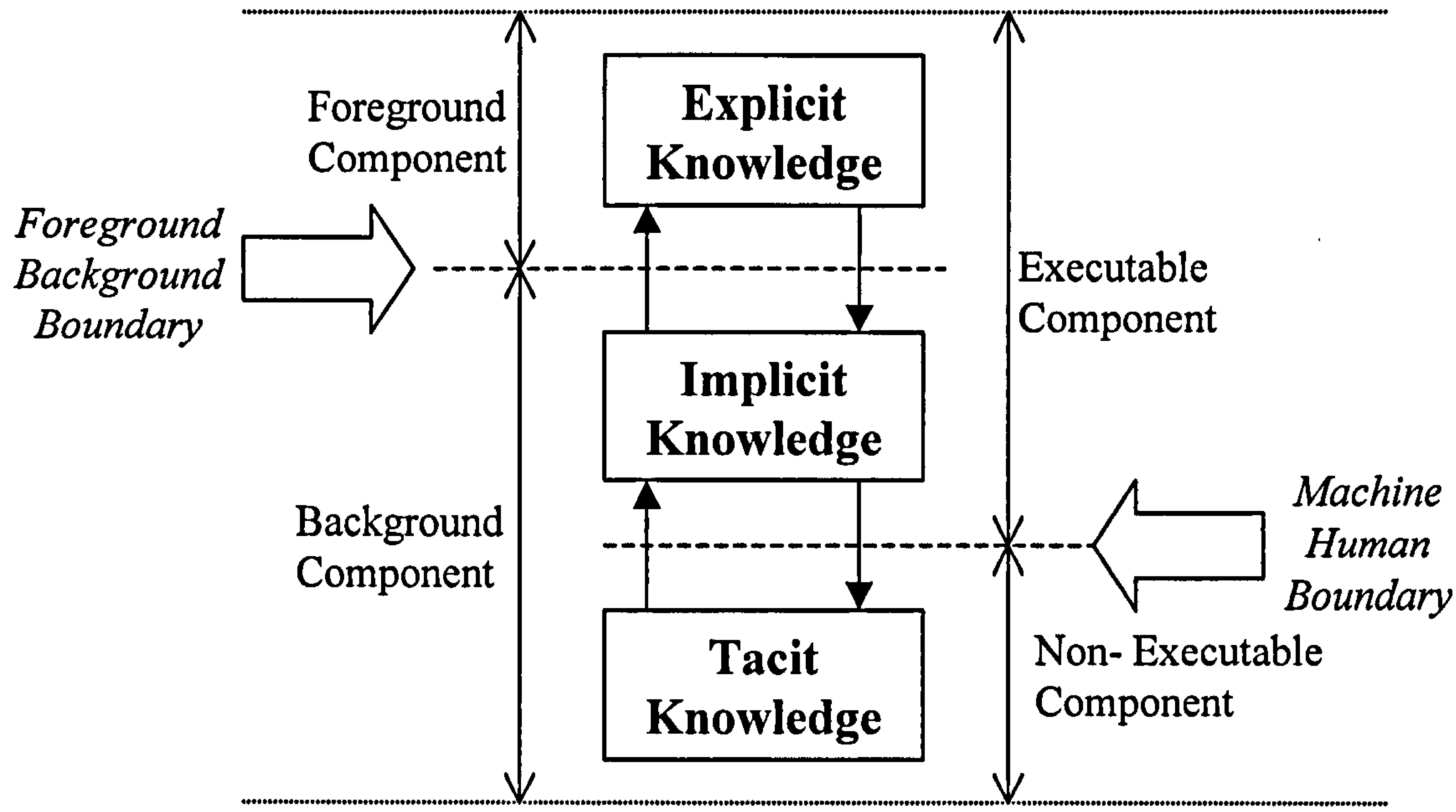


Figure 2-3 Executable knowledge model (Zheng et al. 2001)

2.2.3.5 Others kinds of knowledge

Diverse researchers have explored knowledge trying to understand the different types of knowledge that include the human experience that persons apply solving problems or maximising a job performance. Hannabuss (Hannabuss 1991)explored two kinds of knowledge: a) street knowledge and b) academic knowledge. Meliciani (Meliciani 2002) defined four kinds of knowledge: a) know-what, which is knowledge about facts and can be broken down into bits easily codified, b) know-why, which is knowledge about principles and laws c) know-how, which is skills and the capability to undertake a given task successfully, d) know-who, which is about who knows what and who knows how to do what. Mahe and Rieu (Mahe and Rieu 1998) observed two instances of tacit knowledge: a) context knowledge, which corresponds to a set of cultural and behaviour norms; b) practice knowledge that allows performance of a task efficiently applying the experience acquired. Nickols (Nickols 2000) defined thee additional types of knowledge a) declarative knowledge as an instance of explicit knowledge that consists of descriptions of facts, things, methods and procedures; b) procedural knowledge as an instance of tacit knowledge that display the doing of something and reproduce the manual and mental skills; c) strategic knowledge that is other instance of tacit knowledge refers to the know-when and know-why. Although some authors have been exploring other types of knowledge to obtain understanding about the knowledge in the knowledge management, it was decided to use explicit, tacit and implicit with the types of knowledge representation mentioned above to explore the knowledge maintenance with in KBS. This is because it is believed that these are appropriated for the capture and organisation of manufacturing knowledge.

There are other types of knowledge that can be managed out of the knowledge systems (Ackerman et al. 2003). However, in this thesis only the different types of knowledge that can be structured and managed within KBS are analysed.

2.2.3.6 Knowledge types discussion

Based on above discussion and following Figure 2-4, the common characteristics between explicit and tacit knowledge is the possibility of whether the knowledge can be articulated. If the knowledge is already articulated it is considered explicit knowledge. On the other hand, tacit knowledge is the case when the knowledge cannot be articulated. Implicit knowledge is the knowledge that has not been articulated but it can be articulated. In other words, implicit knowledge is between explicit and tacit knowledge because it can be articulated but hasn't.

The majority of the authors mentioned in section 2.2.3 agree that tacit knowledge is a knowledge type that is not possible to articulate. However, other researches have been working in the creation of tacit knowledge structures to articulate it and support decisions. For example, Herschel et al. (Herschel et al. 2001) noted that although it is problematic to structure tacit knowledge to support decisions, it is possible to do it using knowledge exchange protocols. This argument related to the creation of tacit knowledge structures is in line with Malhotra (Malhotra 2000) and Swap et al. (Swap et al. 2001) works where they suggested the use of patterns and storytelling as an effective method to capture tacit knowledge and enhance knowledge transfer. In addition, Rodhain (Rodhain 1999) applied the technique of cognitive mapping as a graphic representation of individual's model to transform the tacit knowledge into explicit knowledge. The author of this thesis decided to use patterns, storytelling, sketches and video clips to organise tacit knowledge because he considers that it is possible to structure and manage this complex knowledge using these types of knowledge representations. Chapter 4 presents some manufacturing tacit knowledge examples according to the above definitions and discussion.

A major opportunity was identified in the tacit and implicit knowledge because it is not completely clear the differences between these concepts (Balconi 2002) (Nickols 2000). For example, Gardner et al. (Gardner et al. 1996) defined implicit knowledge as the knowledge which people show in their actions but they are unaware, or unable to articulate. However, this definition is closer to the majority of the authors' tacit knowledge definition. As a consequence and according to the above explanation, in this research tacit knowledge is defined as Nonaka and Takeuchi (Nonaka and Takeuchi 1995) did and implicit knowledge as Nickols (Nickols 2000) and Zheng et al. (Zheng et al. 2001) defined. For example, tacit knowledge consists of personal relationships, practical experience and shared values. Implicit knowledge has a bridge property that links together the explicit and tacit components.

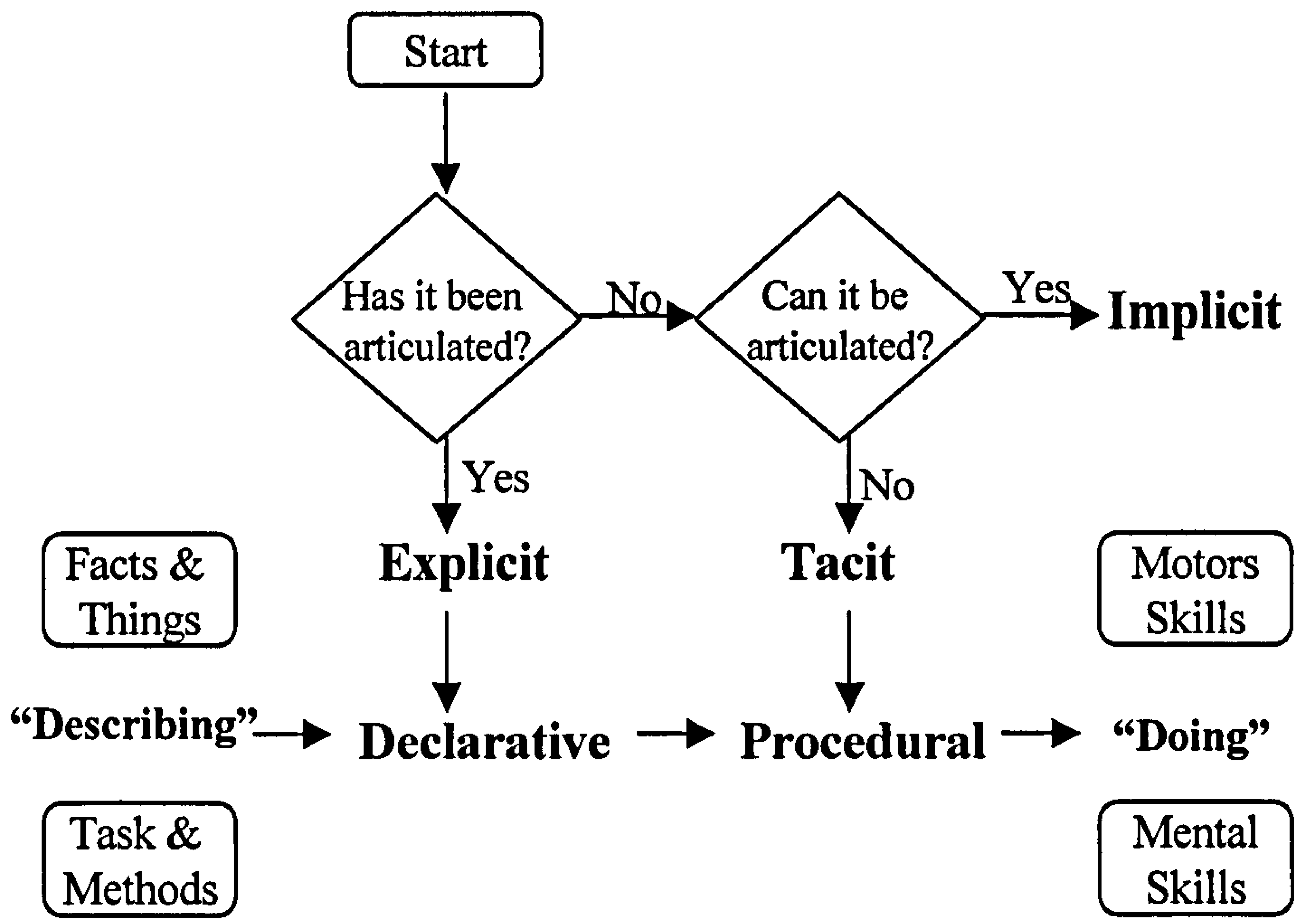


Figure 2-4 A framework about knowledge in KM (Nickols 2000)

Some researchers have established that tacit knowledge can not be articulated (Nonaka and Takeuchi 1995), (Nickols 2000), (Mills and Goossenaerts 2001) and (Zheng et al. 2001). However, other researchers are exploring new techniques to capture and transfer tacit knowledge (Malhotra 2000), (Swap et al. 2001) and (Rodhain 1999). This tacit knowledge exploration gave the author of this thesis the idea to propose the use of patterns, storytelling, sketches and video clips to capture and organise complicated manufacturing knowledge that can not be captured by explicit knowledge representations such as: graphs, tables and procedures. According to this explanation it can be possible to make a difference between explicit and tacit knowledge. However, it is important to give emphasis to the difference related to the implicit knowledge. The author of this thesis decided to use mainly text to represent manufacturing knowledge using implicit knowledge definition. According to the scope of this research and the pilot example explained in the previous paragraph, the author of this thesis uses the implicit knowledge definition to capture new technology knowledge and apply it in machining processes. Chapter 4 presents some manufacturing implicit knowledge examples according to above definitions and discussion.

In summary researchers have emphasised the necessity of methods and tools to manage knowledge' organisation. In addition, other researchers have explored the role of information and knowledge types within KM. However the understanding of different types of knowledge and how these can be structured needs to be expanded. Today there are some decision support systems based on knowledge as a tool to systemise knowledge' organisation. In the next section some of them are presented.

2.3. Decision Support Systems Based on Knowledge

This section has three parts. The first part presents different types of Knowledge Based Systems. The second part provides an overview of Artificial Intelligence Based Systems. The third part presents different knowledge management tools. Decision support systems based on knowledge are important to this work because the raw material for these systems is knowledge that needs to be structured and maintained.

2.3.1. Knowledge based systems

Knowledge is a complex matter and is currently structured using different methodologies and tools improving the decision making process (Grundstein et al. 2003). A Knowledge Based System (KBS) is a software system capable of supporting explicit representations of knowledge in some specific competence domain and exploited through appropriated reasoning mechanism in order to provide high-level problem solving performance (Guida 1994). Knowledge is the raw material in the decision support systems based on knowledge and it is difficult to manage.

The type of KBS is named according to the knowledge structured in the specific domain and the tools used to support the decision making process. Knowledge based engineering systems (KBE) are regarded as specialised type of KBS that perform tasks related to engineering domain (Miao et al. 2002). In addition, the KBS called expert systems are intelligent computer programs that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution (Shi et al. 1999). Expert systems may emulate the abilities of human expert in a particular domain and this term can be misleading as it can imply a greater level of ability than is actually the case (Lovett and Bancroft 2000). However, the knowledge structure and its understanding in a particular domain is a particular problem in the development of these systems.

Cordova and Gutierrez (Cordova and Gutierrez 2000) developed a KBE system organising information related to customer requirements, product functionality, product design and manufacturing process. They utilised information modelling techniques and object oriented software tools to integrate the information and knowledge to support product development decisions. Shi et al. (Shi et al. 1999) created an expert system for the selection of multi-diameter drills combining a rule-based knowledge base, a database and online help including diagnostic working together within a new intelligent windows environment. Shi et al. (Shi et al. 1999), Cordova and Gutierrez (Cordova and Gutierrez 2000) agree that there is a need to move forward the understanding of knowledge structures and representations to improve these systems implementations.

Many of these systems are severely limited by the types of knowledge currently used in knowledge base and database systems technology (Sormaz and Khoshnevis 1997). The nature, diversity and complexity of knowledge require knowledge representation schemas to be as flexible and robust as possible (Gorti et al. 1998). Currently knowledge based systems technology lack the means to provide efficient and robust knowledge bases, while database system technology lacks knowledge representations (Brodie et al. 1986). In the long term, research is needed to find ways for knowledge based system technology to support database systems and vice versa. In the near term, research is needed to develop tools that support the design and development of systems that require an integrated set of knowledge base and database system tools (Sriram and Adey 1987).

The deployment of KBE are now becoming more commonplace in engineering industry (Chapman and Pinfold 2001) and there is a need to ensure that valuable knowledge used in product development is shared properly through the product life cycle (Kochan 1999). As such, there will be an ever-increasing demand to share a common manufacturing product representation (Penoyer et al. 2000). The product knowledge can be managed within a KBE to ensure that the knowledge retains its value and usefulness during the product life cycle. The use of these systems has been for the short-term benefit of the company. However, it is important to consider the longer-term use, emphasising the product knowledge management within knowledge based engineering system by looking at key issues that are related to the longer-term use of the systems (Sainter et al. 2000).

KBE is an engineering tool that represents a merging of object oriented programming (OOP), Artificial Intelligence (AI) techniques and computer-aided design technologies, giving benefit to customise design and manufacturing knowledge (Chapman and Pinfold 2001).

Some researchers have been working with KBS organising information and knowledge to support the product development process. These researchers named in individual manner the systems created and the functionality provided. For example, Zhao et al. (Zhao et al. 2000) created an information-based product development system composed of various components that structure mainly information supporting manufacturing decisions. These components are software applications designed to address certain functions related to: design, analysis, manufacturing, control, and data management. Rezayat (Rezayat 2000) developed a knowledge based product development system for original equipment manufacturers (OEM's), placing emphasis on the huge amount of knowledge that annually (OEM's) obtain, leading to a major need for capturing and maintaining their knowledge for later use. Sheremata (Sheremata 2002) noted that high level of knowledge generation and integration is required in the development of software new product development. This is notoriously difficult when trying to integrate large amount of creative ideas, in-depth knowledge and accurate information. However, Zhao et al. (Zhao et al. 2000), Rezayat (Rezayat 2000) and Sheremata (Sheremata 2002) agree that due the large amount of information and knowledge created it a method is required that improves the knowledge structures to allow future knowledge maintenance.

There is an increasing recognition that the core knowledge of an engineering organisation is a valuable asset, and the time and effort invested in using it efficiently and effectively will return generous dividends (Gupta 2001). Several software products are now mature enough to make KBS relatively affordable for an increasing number of companies, but a major risk is derived from the lack of methodology and the absence of appropriated support for the KBE application life cycle (Fu et al. 2000). Therefore, if this scenario is to change, a comprehensive methodology is required to continuously support activities from domain knowledge elicitation to application validation and maintenance (Aziz et al. 2002).

2.3.2. Artificial intelligence based systems

An additional tool for decision support systems based on knowledge is Case Based Reasoning (CBR). CBR systems are considered a general paradigm to AI characterised by its capability to capture past experiences and knowledge for case matching in various applications, which are an emerging and well-accepted approach in the implementation of knowledge management systems (Lau et al. 2003). CBR systems provide new solutions by analogy of past design situations, based on adaptations of the previous selected solutions (Costa 2000). It soon became obvious that to tackle KM well, contributions from, among others, diversified areas spanning management, human resources, marketing, AI and knowledge modelling are needed (Tsui et al. 2000).

KM covers the aspects mentioned in section 2.2. However, the role of AI in KM is important because the cultural and human resources issues should be considered as well as the devolvement of intelligence that enhance the performance and execution of the ever increasing, common knowledge-intensive task facing organisations today (Tsui et al. 2000).

Different researchers have developed decision support systems based on information and knowledge using AI tools to support manufacturing decisions and extending the participation to KM initiatives. For example, Worley et al. (Worley et al. 2002) developed a system that allows the implementation of workflow and groupware facilities and the communication between modules is achieved through a database which provides the integration with the main information system. Grundstein (Grundstein 1994) applied AI methods and techniques to capitalise company knowledge to work more effectively supporting knowledge transfer. Shehab and Abdalla (Shehab and Abdalla 2002) developed an intelligent knowledge based system for product cost modelling using AI and object-oriented tools. This system has the capability of selecting: a) material, b) machining processes, and c) parameters; based on a set of design and production parameters. As a result, the system estimates the product cost throughout the entire product development cycle including assembly cost. Noh et al. (Noh et al. 2000) created a CBR approach to cognitive map-driven tacit knowledge management. However, Worley et al. (Worley et al. 2002), Grundstein (Grundstein 1994), Shehab and Abdalla (Shehab and Abdalla 2002) and Noh et al. (Noh et al. 2000) agree that work with knowledge is a difficult task and it is important to move forwards the exploration of new ways for knowledge representations, particularly with tacit knowledge.

2.3.3. Knowledge Management Tools

This section presents ranges of diverse approaches that are currently used in decision support systems based on information and knowledge as a tool to support KM. Some of these approaches are: agents, ontologies, data mining and XML. However there are others that include some of these approaches but are commercial KM tools. Agents, ontologies, data mining, XML and commercial KM tools are presented in the next paragraphs. The KM tools presented in this section are important in this thesis because they require efficient information and knowledge structures to support decisions.

KM has recently received considerable attention in the computer information systems community and is continuously gaining interest by industry, enterprises and government (Metaxiotis et al. 2003). As we move toward building knowledge organisations, KM in combination with information management will play a fundamental role in the success of transforming individual knowledge into organisational knowledge (Metaxiotis et al. 2002).

Today's knowledge workers are expected to carry out tasks and solve problems that facilitate the effective and efficient product manufacture. Numerous information technology-based systems have raised knowledge workers productivity (Wu 2001). Software agents are programs that perform specific tasks on behalf of their users (Syed 1998). They are distinguished from other types of software by their ability to complete assignments independently without intervention or manipulation by the user (West and Hess 2002). Different authors are working with software agents and multi-agent systems organising KM in complex processes such as manufacturing, supply chain etc, in order to increase the effective decisions and save time (Barthes and Tacla 2002) .

Decision support and KM processes are interdependent activities in many organisations and in all cases; decision makers always combine different types of data and knowledge available in various forms in the organisation. In most of cases the key issue in the decision-making process is the knowledge structures to allow future knowledge maintenance (Metaxiotis et al. 2003). Figure 2-5 depicts an agent-based framework for managing knowledge at work emphasising the knowledge workers with a magnifying glass. The authors mentioned above working as with agents agree that the definitions and understanding of information and knowledge structure are required for efficient system development and effective agent communications.

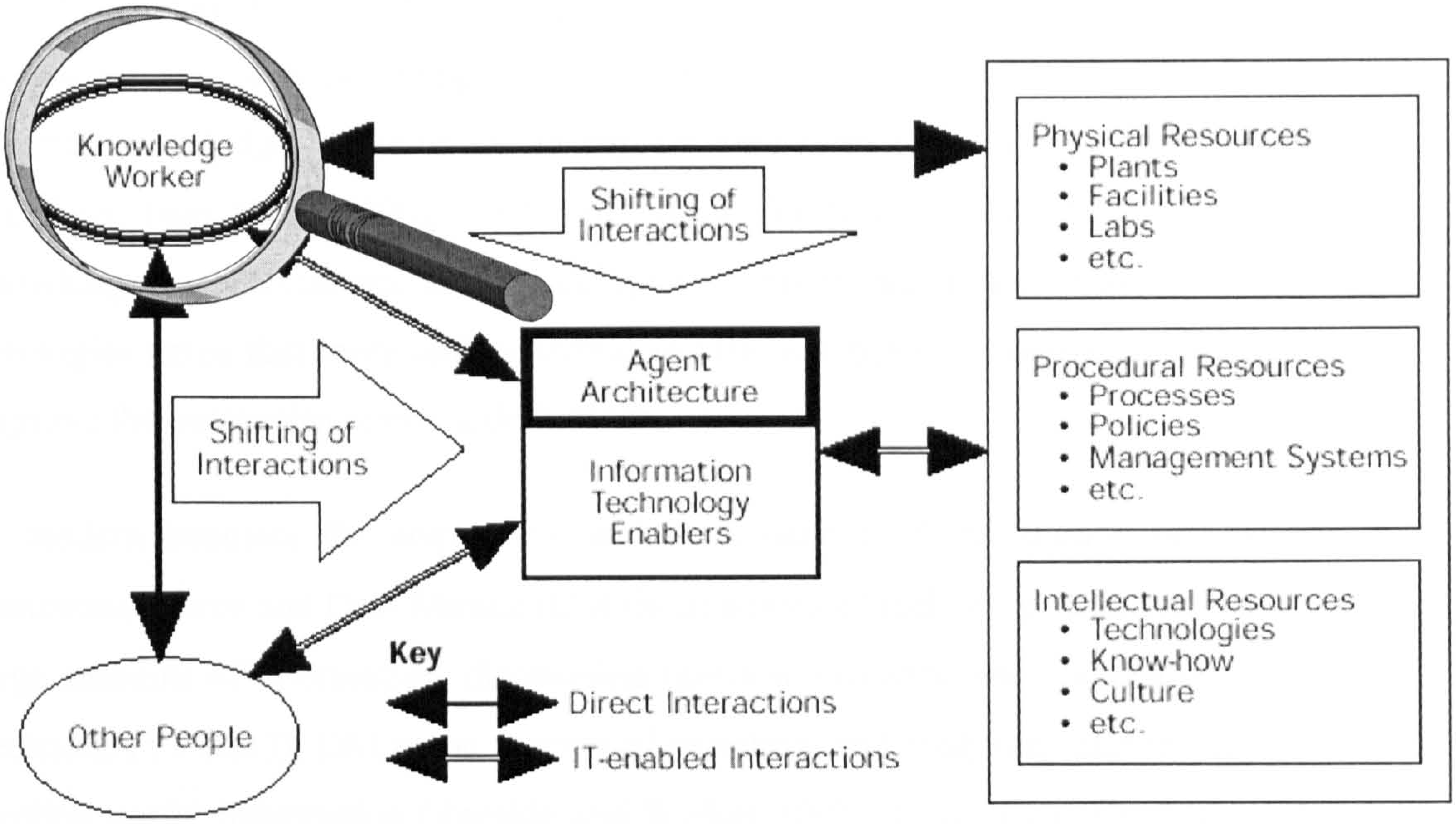


Figure 2-5 Agent-based framework for managing knowledge at work (Syed 1998).

An ontology is a formal explicit description of concepts in a domain of discourse that defines a common vocabulary for researchers who need to share information in a domain (Yeh et al. 2003). An ontology is an explicit specification of a conceptualisation (Gruber 2003). It is a declarative representation including the vocabulary for referring to the terms in a subject area and the logical statements that describe what the terms are, how they are related to each other, and how they can or cannot be related to each other (Fensel 2002). Ontologies provide a vocabulary for representing and communicating knowledge about some topic and a set of relationships that hold among the terms in that vocabulary (Akkermans 2003).

Some of the reasons for developing an ontology are: a) to share common understanding of the structure of information among people or software agents, b) to enable reuse of domain knowledge, c) to make domain assumptions explicit, d) to separate domain knowledge from the operational knowledge, d) to analyse domain knowledge (Yeh et al. 2003).

Different authors have explored decisions support systems based on information and knowledge using ontologies and agents. Chung et al. (Chung et al. 2003) developed a KBS exploring the use of ontologies and agents to provide support in the area of new product development within chemical industries. Maedche et al. (Maedche et al. 2003) described an integrated enterprise-knowledge management architecture for implementing an ontology-based knowledge management system. Smirnov et al. (Smirnov et al. 2003) created an approach providing a mechanism to allow decision makers to have their required knowledge "at hand" in an appropriated form for making correct and timely decisions. Hori (Hori 2000), Yu-N and Abidi (Yu-N and Abidi 2000) explored tacit knowledge representations using ontologies. Authors mentioned above working with ontologies agree that more understanding in different types of knowledge is required to improve the ontologies research definitions.

In modern business the acquisition and management of information has become a competitive force and Data Mining (DM) is an advanced technology tool that can process large amounts of information, discovering useful information and knowledge to support decisions (Ye 2003). DM is the process of searching and analysing data in order to find implicit useful information (Raeside and Walker 2001). It involves selecting, exploring and modelling large amounts of data to uncover previously unknown patterns, obtaining comprehensible information from large databases (Dennis et al. 2001). DM uses a broad family of computational methods that include statistical analysis, decision trees, neural networks, rule induction and refinement, and graphic visualisation (Shaw et al. 2001).

Knowledge discovery and learning is an iterative process that extends the collection of DM techniques into a KM process (Shaw et al. 2001). The term knowledge discovery in databases (KDD) was coined to represent the process by which resources are applied towards the transformation of available data into strategic information (Bendoly 2003). The discipline encompasses research including the study and development of DM tools (Neaga 2003). DM systems can discover various types of knowledge, including association rules, characteristics rules, classification rules, clustering, evolution, and deviation analysis (Lee and Siau 2001). Using advanced information technologies, KDD can uncover veins of surprising and golden insights in a mountain of factual data (Gargano and Raggad 1999). Although the knowledge can be generated by DM tools, the clear definition of the knowledge elements depicted in Figure 2-6 is necessary to maximise the effectiveness of the KM process (Shaw et al. 2001)

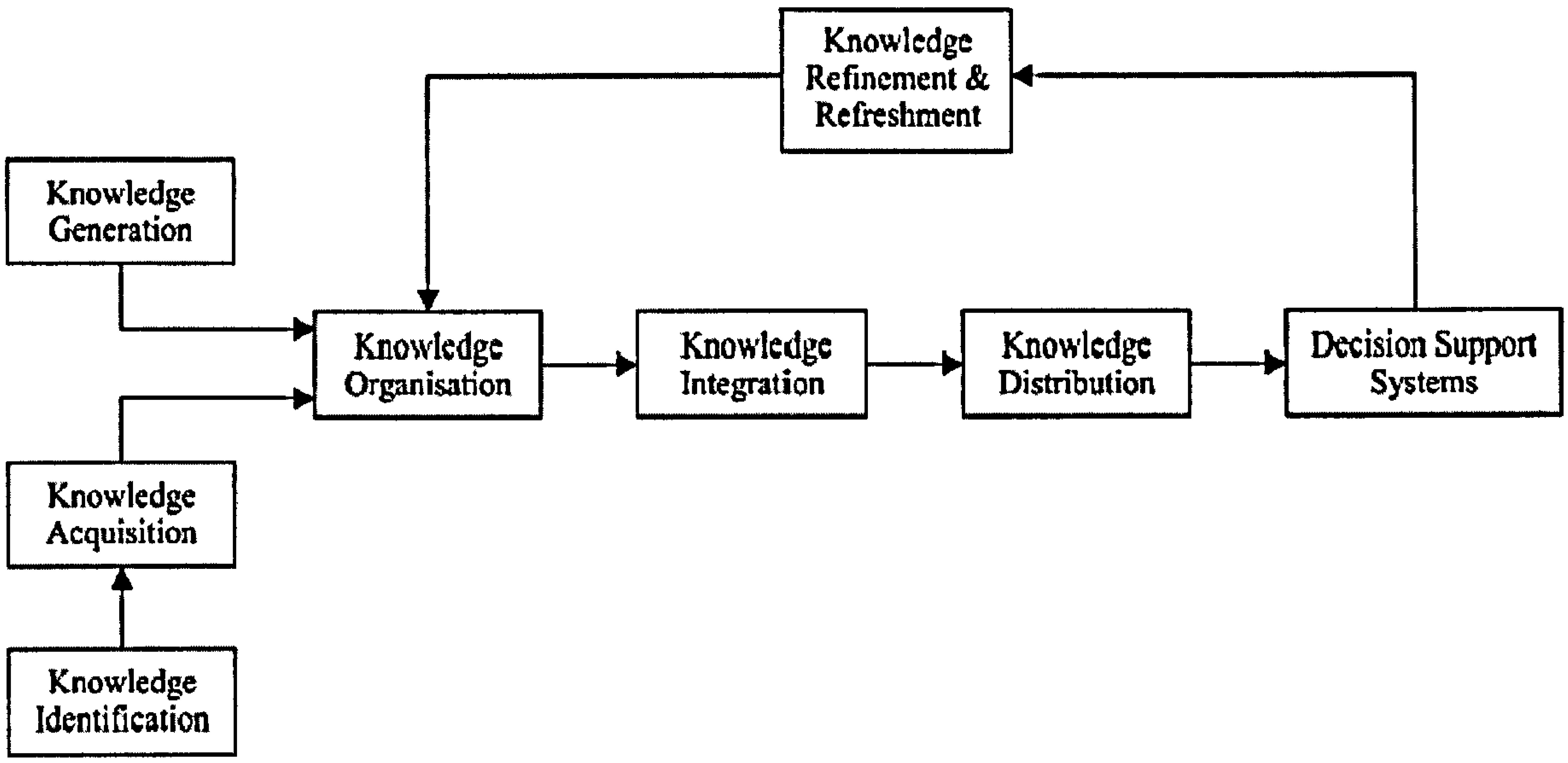


Figure 2-6 Stages of knowledge processing (Shaw et al. 2001) (Metaxiotis et al. 2003)

Different researchers are used eXtensible Markup Language (XML) to create software tools to support KM and knowledge discovery. XML is a data format for structured document interchange on the web (Lau et al. 2001). A markup language is a mechanism to identify structures in a document (Boury-Brisset 2000). The XML specification describes a class of data objects called XML documents, and partially describes the behaviour of computer programs that process them (Roucoules et al. 2002). XML provides a flexible markup standard for representing data models and KM provides IT processes for capturing maintaining and using information (Otto et al. 2001). While the processes that comprise KM and the mechanism that form XML differ greatly in concept, they both deal in fundamental with information (Lang and Burnett 2000).

XML was used to create decision support systems based on information and knowledge. Roucoules et al. (Roucoules et al. 2002) developed a system that integrates and manages manufacturing knowledge in design using XML. Lang and Burnett (Lang and Burnett 2000) created a system embracing a diversity of knowledge sources, such as: databases, web-sites, employees, and partners; cultivating the knowledge where it resides, while at the same greater meaning through its relation to other information in the enterprise was given. It is possible to create decision support systems based on knowledge using XML embracing large amount of manufacturing information and knowledge. However, these systems are not good enough because present limitations in the definition of information and knowledge structures which are important for the manufacturing knowledge maintenance.

There are different commercial KM software tools based on information and knowledge organised to support decision. These commercial software use some of the concepts, tools and techniques mentioned in section 2.3. For example: invention-machine is a knowledge based innovation tool that helps engineers and corporations to state engineering problems correctly, create new engineering concepts and manage technical knowledge (Hollingum 1998) .Some similar commercial KM software tools are:

a) Entrieva http://www.entrieva.com/entrieva/index.htm

b) Verity http://www.verity.com

c) Excalibur http://www.excalib.com

d) Autonomy http://www.autonomy.com

However, these commercial KM software tools need the exploration and understanding of new types of knowledge and new information and knowledge structures to make better the functionality of these systems and improve the decision making process (Hollingum 2000) .

In summary different tools and systems are used in the decisions support systems based on knowledge according to the particular domain. The research presented in this thesis deals with manufacturing knowledge and the most generally applicable area for manufacturing knowledge in terms of making decisions about how to make things is process planning. Process planning is used in order to explore a structure of knowledge by the use of a KBS. However, due to the significant volume of knowledge generated in the manufacturing and design stage, there is a need for an efficient, systematic, unambiguous approach to structure and maintain the knowledge in order to assure the long-term use of these systems. In the creation of the decisions support systems based on knowledge an important stage is the information and knowledge modelling that is explained in the next section.

2.4. Information and knowledge modelling

2.4.1. General issues

The development and manufacture of products requires a wide range of information to support the decision-making processes involving different stages of the product life cycle (Costa 2000). The capture, representation and maintenance of this information has become an important aspect for companies (Costa and Young 2001). Information modelling is a useful technique to organise and represent manufacturing information to support decisions (Dorador 2001). Today this subject becomes more critical due the need to share reliable information and knowledge about product, manufacturing resources, processes, etc; (Costa and Young 2001).

As previously defined in section 2.2.2, and according to the definitions of knowledge there are clear differences between information and knowledge. As a consequence it is important to understand differences between information and knowledge modelling (Costa 2000). In the next paragraph a model concept is presented.

The information and knowledge can be organised and represented though models (Costa 2000), (Kakabadse et al. 2003). According to ISO (International Standard Organisation, 1997) a model is a *representation of description of an entity or a system, describing only the aspects considered to be relevant in the context of its purpose*. Models are used to capture the essential features of a real system by breaking them down into more manageable parts that are easy to understand and to manipulate (Savolainen et al. 1995). A model is a simplification of reality (Booch et al. 1999).

According to the model definitions presented, the author of this thesis is explaining two main areas where researchers are exploring information and knowledge modelling: 1) knowledge modelling in KM, and 2) information and knowledge modelling using object-oriented (O-O) methods to develop decision support systems. The author of the research presented in this thesis worked in the second area. However, used the first area to consider the knowledge modelling in KM state of the art to apply it in the creation of new information and knowledge models to develop decision support systems.

1) Knowledge modelling in KM.

Different researchers have done knowledge modelling to get an understanding of the source of knowledge, the inputs and outputs, the flow of the knowledge and the impact of the organisational knowledge management (Davenport 2000). Knowledge modelling is applied to both nature and human beings (Zheng et al. 2001). A deeper understanding of KM complexity requires a multi-modelling and multi-disciplinary approach treating knowledge in its own particular manner (Kakabadse et al. 2003). In the next paragraph some KM models are presented.

Relevant knowledge models were studied in the literature reviewed. Nickols (Nickols 2000) presented in Figure 2-4 a model showing different types of knowledge that can be used in KM. Zheng et al. (Zheng et al. 2001) depicted in Figure 2-3 a model presenting a new dynamic model for knowledge in KM analysing problems and relevant restrictions. Beckett (Beckett 2001) developed a model of a "corporate memory" that defines a repository for information and knowledge beneficial for the future operation of an organisation. Koskinen (Koskinen 2003) created a model to tacit knowledge evaluation in work units. Carneiro (Carneiro 2000) obtained a conceptual model of KM efficiency in the organisations supported by different applications. The analysis of these models provided an idea about the importance of the knowledge modelling in KM giving understanding of different types of knowledge definitions and interactions in an organisational KM.

2) Information and knowledge modelling using O-O methods to develop decision support systems:

Information and knowledge modelling is important for the creation of decision support systems based on knowledge (Costa 2000). Within these systems, conceptual modelling is important in the understanding of working mechanism such as: tasks, methods, how knowledge is inferred, the domain knowledge and its schemas (Abdullah et al. 2002). In the next paragraphs different knowledge models are presented.

Manjarres et al. (Manjarres et al. 2002) developed a knowledge model reuse to create a decision support system for a medical research application. Abou-Zeid (Abou-Zeid 2002) developed a new knowledge management reference model, providing an O-O framework for the creation of a knowledge management system identifying new organisational knowledge and its relationships. Choi et al. (Choi et al. 2000) created a knowledge model in a computer integrated manufacturing environment allowing the knowledge representation of an information system. The analysis of these knowledge models provided an idea about the importance of the knowledge modelling to develop decision support systems.

The research presented in this thesis is pursuing a contribution in the research idea presented in Figure 2-7 using information and knowledge modelling providing new information and knowledge models to support manufacturing decisions (Young et al. 2001).

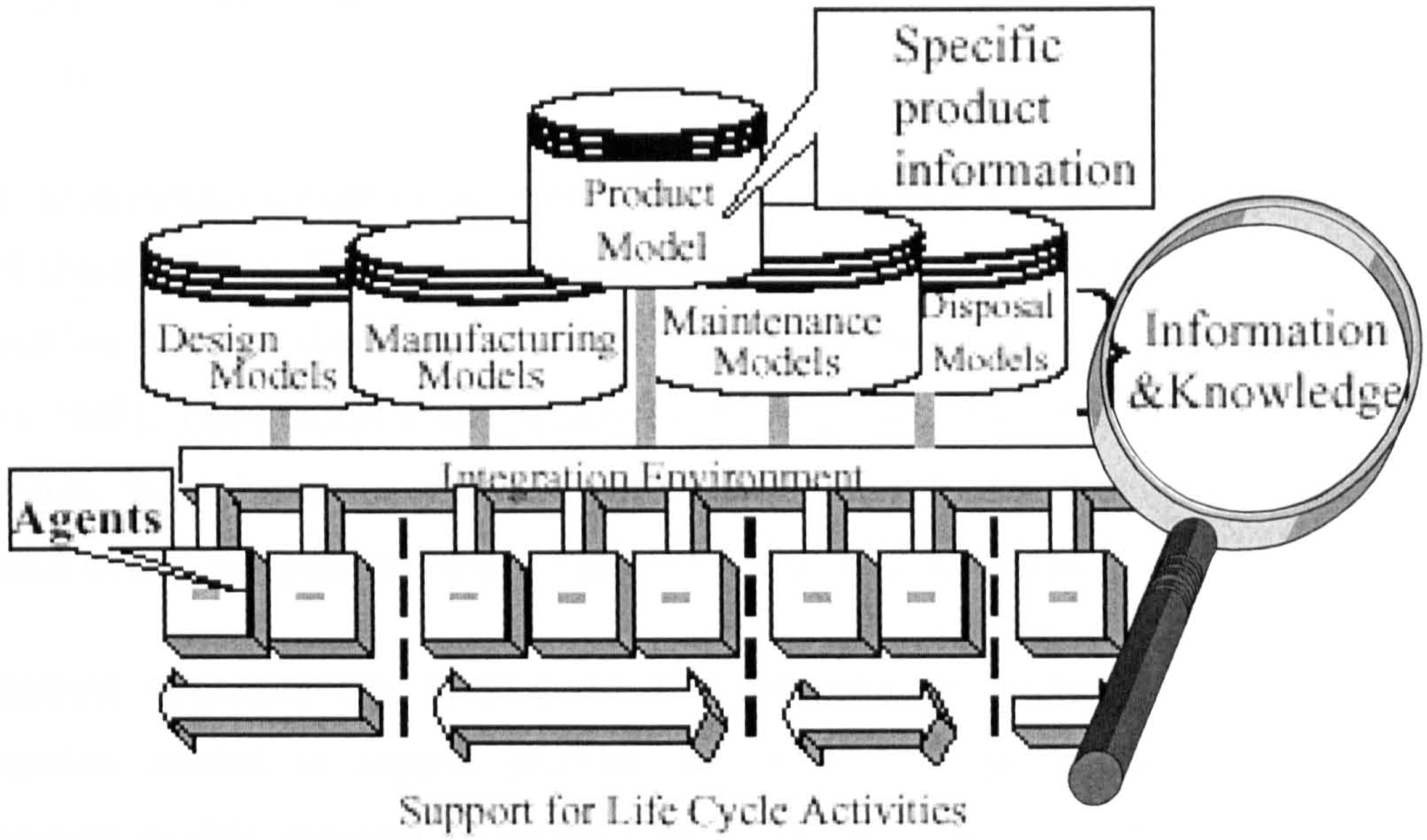


Figure 2-7 A shared information/knowledge research concept (Young et al. 2001).

In summary, four main points can be emphasised: 1) Knowledge modelling in KM has shown wide exploration in organisational KM providing different types of knowledge definitions. 2) Information and knowledge modelling using O-O methods to develop decision support systems are used in different research areas. 3) The research concept presented in Figure 2-7 is based on substantial research work mainly in information modelling to support design and manufacturing decisions. 4) A research question is how to create new information and knowledge models which can support interactions between functional design and design for manufacture. According to these four points, the research reported in this thesis explored different types of knowledge and they were used in the knowledge structures designed. The knowledge structures designed were used to create a MFIKM to support manufacturing decisions, i.e. process planning.

2.4.2. Concepts and standards

The importance of information modelling is widely recognised by the computer integrated manufacturing research community (Dorador 2001). Information modelling and intelligent support tools help define product specifications focused on fulfilling customer requirements and facilitating information sharing between members of extended design teams (Harding et al. 2001).

In information and knowledge modelling it is important to define different main concepts, modelling methodologies, modelling languages, modelling references architectures and ISO standards for modelling data. These points are presented in the next paragraphs.

Information models consist of two main components, the structure model and the process model (Flynn 1996). The structure model describes the organizational elements in an information structure describing the attributes and relationships for a particular entity (Costa 2000). The process model describes the sequence of elements concerned with processing the information and is represented commonly by flow chart diagrams. (Dorador 2001). The purpose of modelling is to predict the behaviour of the system.

Information structures are focused on the provision of shareable sources of all information needed to support product development design teams. However, the information models required go beyond the traditional concept of models providing shared support to all aspects of the product life cycle (Costa and Young 2001). Information structures have been recognised as an area of research where effective results would give wide ranging implications for improved business performance (Dorador 2001). The magnifying glass depicted in Figure 2-7 represents this area of research.

Traditional and Object-oriented (O-O) are two modelling metrologies commonly used in information and knowledge modelling (Flynn 1996). The traditional method has been used over the past twenty to thirty years and has been used on the majority of software tools currently available to support systems development (Martin 1990). O-O methods have emerged in 1990's with certain advantages over the traditional method (Flynn 1996).

The (O-O) method identifies objects, operations and functions from an application domain. The fundamental construct is an object with data structured and functions. The information structures in the O-O model are object classes, attributes, operations and relationships (Booch 1994).

In this research, the O-O methodology is used in the information and knowledge modelling because has the following advantages: easy modelling of complex objects, better extensibility, easy integration with programming code (Booch 1994), (Costa 2000), (Dorador 2001).

Modelling languages provide various manners of formally present an information model (Dorador 2001). IDEF, EXPRESS, and UML are formal and standardised information modelling language commonly used (Costa 2000), (Dorador 2001).

The ICAM Definition (IDEF) language was developed from the U.S. Air Force ICAM program. IDEF modelling language includes different modelling methods: IDEF0, IDEF1, IDEF1X, IDEF2, IDEF3, IDEF4 and IDEF5. In general IDEF methodology is a structured approach to enterprise information and process modelling and analysis (Dorador and Young 2000), (IDEF 2003).

EXPRESS is a part of a suite of standards informally known as STEP that enables information structures to be defined as well as information constraints. It was introduced in early 1990 and was created as ISO 10303-11 for formally specifies information requirements of product data model (Fowler 1995).

In recent years, the use of O-O technology has increased significantly in the area of integrated information systems through the use of programming tools and methods such as UML (Costa et al. 2001). UML is a standard modelling language for visualising, specifying, constructing and documenting object-oriented systems (Booch et al. 1999).UML is called a modelling language, not a method. The modelling language is the (mainly graphical) notation that methods use to express design. The process is their advice on what steps to take in doing a design. The modelling language is the most important part of the method. It is certainly the key part for communication. If you want to discuss your design with someone, it is the modelling language that both of you need to understand not the process you used to get that design (Flower and Scott 2000). The UML is appropriate for modelling systems ranging from enterprise information systems to distributed Web-based applications and even to hard real times embedded systems. It is a very expressive language, addressing all the views to develop and then deploy such systems (Booch et al. 1999). The main O-O programming concepts are explained in appendix A.

The appropriate combination of the three information modelling language explained above is required to develop complex applications (Dorador 2001). However, in this research IDEF0 and UML was enough for the information and knowledge modelling.

ISO TC184/SC4 DATA AND LANGUAGES FOR MANUFACTURING APPLICATIONS			
1. DIGITAL PRODUCT DATA REPRESENTATION	**2. MANUACTURING MANAGEMENT DATA**	**3. PARTS LIBRARY REPRESENTATION**	**4. PARAMETER REPRESENTATION**
ISO 10303 Industrial Automation Systems and Integration *-Product data representation exchange*	**ISO 15531 Industrial Automation Systems and Integration *-Industrial manufacturing Management data***	**ISO 13584 Industrial Automation Systems and Integration *- Standard for the Representation of standard parts***	**ISO 14959 Industrial Automation Systems and Integration *- Parametric***
ISO 10303-1 Overview and fundamental principles	**ISO 15531-1 Overview**		
ISO 10303-44 Product structure configuration	**ISO 15531-42 Time model**		
ISO 10303-240 Application protocol: *process plan for machined products*			

Figure 2-8 The TC184/SC4 work divided in four areas (TC184/SC4 2003).

The development of information systems to support design and manufacturing activities has three key aspects to be addressed: a) the structure of the information, b) the management of the information, and c) the functionality of the applications programs, which use the information (Young et al. 1999). In order to support the development of information systems to advance design and manufacturing with in integrated environments reference models, open system architectures and standard notation are used as the basis for their implementation (Costa et al. 2001). The ability to harmonise these different viewpoints is a significant step forward in information system design (Molina and Bell 2002). The modelling reference architectures were widely explained and used by previous researchers such as: Costa (Costa 2000) and Dorador (Dorador 2001).

In the organisation and classification of different types of information it is important to consider the ISO standards for modelling data. TC184/SC4 group in the ISO is concerned with standardisation in the field of data and languages for manufacturing applications. SC4 is developing standards that provide capabilities to describe and manage industrial product data throughout the life of the product (TC184/SC4 2003). Figure 2-8 represent the work of the TC184/SC4 group divided in four areas.

In recent years a lot of research works have been reported on information modelling to support decisions and two main information models have been widely explored: the product model and the manufacturing model (Dorador 2001). In the next sections the recently works related with these two models are discussed.

2.4.3. Product modelling

There are several definitions of product model but two are considered as a reference in this thesis because they are the most appropriate for the manufacturing structures designed: a) a product model is a computer readable representation of all product related data (Bell and Young 1992).b) a product model has an structure that provides a source and repository for information concerning a product under development (Zhao et al. 2000).

The design of a product development information system involves the definition of the information structures that are needed to support design and manufacture. The product data model describes the structure of the information related to a product throughout its life cycle (e.g. specifications, geometry, etc.) (Zhao et al. 1999). Product modelling aims to provide a consistent representation of products information that can be reached and used by one or more software systems during all stages of product design and manufacture (Costa 2000).

Different researchers have used the product model concept. For example, Costa (Costa 2000) developed new product range model included in the product model structure and Dorador (Dorador 2001) expanded the understanding about the product model for product and process information and interactions for assembly decision support systems. The manufacturing model concept is presented in the next section.

2.4.4. Manufacturing modelling

The concept of manufacturing model has been evolved from efforts of various industries and research groups to build information models for their particular applications (Molina and Bell 1999).A manufacturing model concept was first defined by Al-Ashaab (Al-Ashaab 1994) as the model that captures the information which describes the characteristics or behaviour of: a) the process, b) knowledge, and c) constraints; that governs the use of the processes. This manufacturing model represents the capabilities of the injection moulding process. The concept was later used by Molina et al. (Molina et al. 1995) defining the manufacturing model as an information model that describes the manufacturing capability of a particular facility. The model obtained consists of three types of information: manufacturing resources, processes and strategies; in four levels of manufacturing facilities (i.e. Factory, Shop, Cell, Station). The high-level Booch class representation of the manufacturing model is depicted in Figure 2-9.

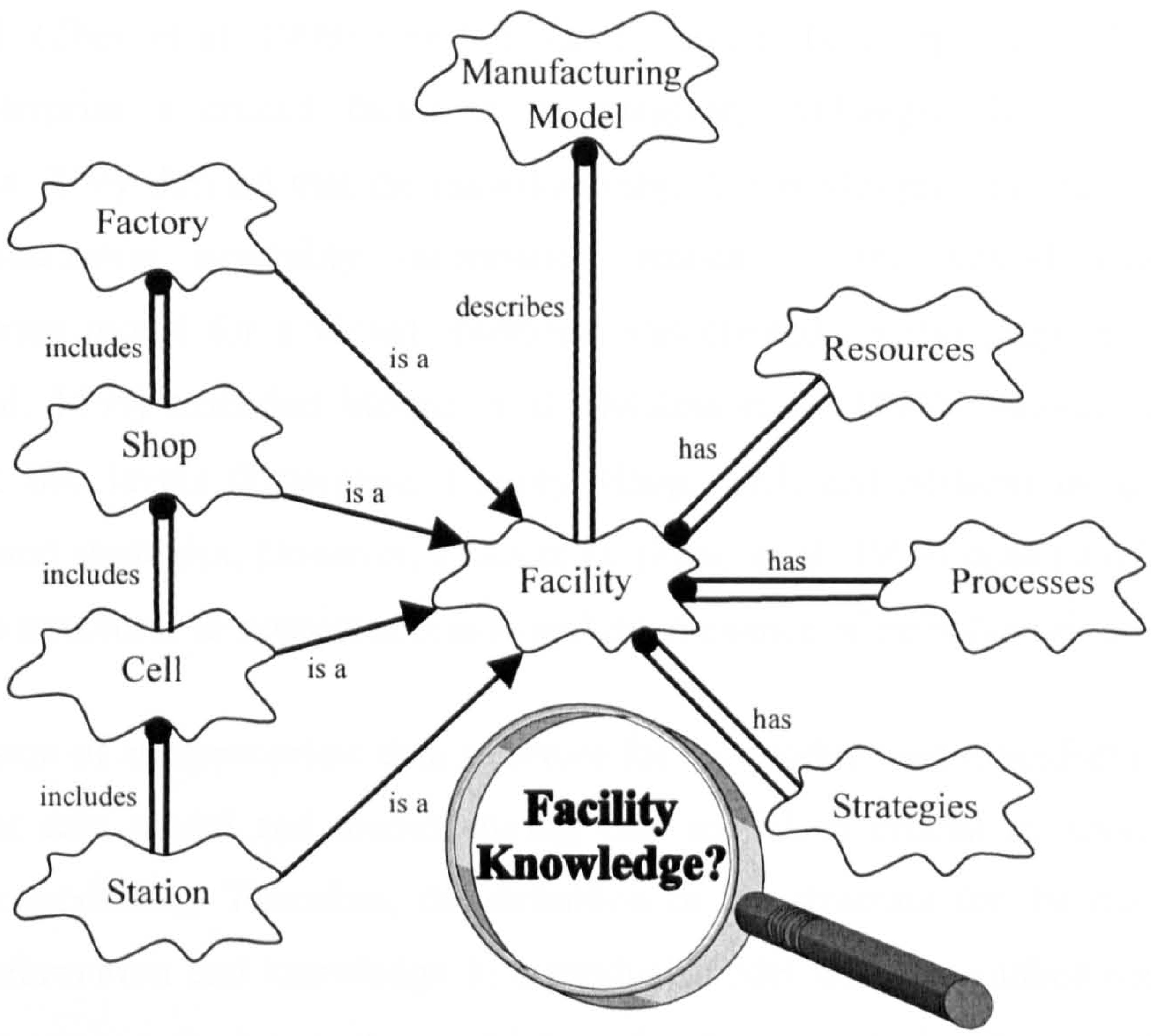


Figure 2-9 High-Level Booch class representation of the manufacturing model (Molina and Bell 1999).

Molina and Bell (Molina and Bell 1999) work identified that strategies represent how company resources and processes are organised, composed, and deployed to support the realisation of the manufacturing function, in order to achieve the manufacturing objectives of the facility. However Molina and Bell did not explore how the facility knowledge is structured in the manufacturing model in order to support access to and maintenance of manufacturing knowledge. This is defined as a critical issue in the research presented in this work.

Strategy class organises processes and resources determining how to use them in a particular manufacturing function (Molina et al. 1995). This strategy class stores manufacturing knowledge. However it was decided to organise the manufacturing knowledge using a new knowledge structure because the knowledge related to processes and resources within a manufacturing facility was required to be structured. The manufacturing knowledge determines use of strategies and strategies apply manufacturing knowledge (Guerra and Young 2002). This thesis is mainly focused on how to organise the manufacturing knowledge with a maintenance objective. The strategies can be more related to the use of the manufacturing knowledge stored. For example, two strategies can use the same piece of knowledge.

Zhao et al. (Zhao et al. 1999) reported that to ensure the competitive advantage of a virtual enterprise a crucial factor is to integrate, exchange, share and distribute information. They defined that the manufacturing data model provides the structure for the manufacturing capability information related to the virtual enterprise. A manufacturing model for a virtual enterprise was created for this purpose. Zhao et al. (Zhao et al. 1999) extended Molina et al. (Molina et al. 1995) manufacturing model concept at five levels (Enterprise, Factory, Shop, Cell, and Station) using resources, processes and strategies. However, Zhao et al. (Zhao et al. 1999) didn't explore facility knowledge structures to support access to and maintenance of manufacturing knowledge.

The provision of an appropriate data structure for the product and manufacturing model, i.e. product data model and manufacturing data model, is crucial in information and knowledge modelling. Therefore, the definition of the structure for the manufacturing relevant information and knowledge in a product model and a manufacturing model is essential to support the integration and interaction between design for manufacture and post design process planning (Zhao et al. 2000).

Harding (Harding 1996) created a knowledge representation model (KRM) providing a sound basis for the creation of necessary software applications in Concurrent Engineering (CE) environment. The KRM facilitates the capture, interpretation and implementation of important aspects of types of expertise. However, Harding emphasised that KRM limitation is the changing value of knowledge over time. That is, there is currently no in-built metrics for evaluating worth of knowledge, and prioritising its use.

Costa and Young (Costa and Young 2001) observed that the categorisation of different types of information and knowledge are important in dealing with the development of information models. However, the definition of the information and knowledge structures required are important (Dorador 2001).

It is worth emphasising that the Manufacturing Information Research Group at Loughborough University have made substantial contribution in this area (Al-Ashaab 1994), (Molina et al. 1995), (Harding 1996), (Zhao et al. 2000), (Dorador 2001). However, others researchers have also explored the manufacturing model concept. For example Giachetti (Giachetti 1999) proposed the use of a standard manufacturing information model to support the product realisation process. The entire manufacturing model structure is organised by a manufacturing firm that has manufacturing process specification. The manufacturing process specification is characterized by manufacturing process capabilities, is enabled by manufacturing resources and is dynamically described by physical manufacturing process model. Giachetti and Alvi (Giachetti and Alvi 2001) explored an EXPRESS object oriented manufacturing model of the manufacturing equipment and manufacturing process capabilities. This manufacturing model was applied for manufacturability analysis of printed circuit board fabrication.

2.4.5. Knowledge Maintenance

The majority of researchers seem to suggest that manufacturing knowledge management and maintenance is an important issue in the decision support systems based on knowledge. Mills and Goossenaerts (Mills and Goossenaerts 2001) stated it is important to understand what knowledge is necessary to the product realisation process and to move towards thinking of and implementing a knowledge structure and product knowledge management. Beckett (Beckett 2001) suggests that intellectual assets are more important than tangible assets in effectively achieving the aims of an organisation in the 21st century. Under those circumstances, intellectual assets are developed using knowledge and learning processes emphasising knowledge value. Young (Young 2003) identified that although advances in the use of computer systems in product design and manufacture have been significant in recent years, the necessity to develop flexible systems that can be readily maintained with up-to-date information and knowledge still exists.

Information Technology has two major capabilities: a) the ability to perform rapid calculations, and d) store and retrieve information. As a result, a major limitation of this type of approach is the maintenance of a processing capability within decision support systems based on information and knowledge. There is a significant difference between text-based information, which can be understood by an individual, and structured information, which can be structured by a software application. Providing well-structured information is critical to the success of information support systems in the future (Young 2003).

Understanding how to structure and maintain the manufacturing information and knowledge that supports key decisions in concurrent engineering is critical to the future decision support systems based on knowledge (Zhao et al. 2000).

The creation of knowledge structures to support manufacturing knowledge maintenance is important. However it is convenient to define knowledge maintenance and its relationship with knowledge structures. A significant relationship was found between knowledge categorisation and the creation of knowledge structures in order to obtain knowledge maintenance. To explore the course of action of updating knowledge it is essential to create an understanding of different knowledge categorisation and to define a suitable knowledge structure. In this case, knowledge maintenance means the practice of updating the types of knowledge within a manufacturing knowledge structure.

2.5. Summary

The literature review reported in this chapter provides a survey on the main areas related to this research.

Knowledge Management is an important element in the creation of knowledge structures for the collective manufacturing expertise and using them to support decisions through knowledge codification allowing a continued learning. The understanding of knowledge codification is achieved by the consistent definition of data, information and knowledge, which must be taken into consideration for the creation of new knowledge types. Although the KM concept is associated with knowledge models to structure knowledge, additional knowledge models can be defined to support the development of decision support systems based on manufacturing knowledge.

Decision support systems based on knowledge are an important part in the decision making process, where today different tools are used according to the particular domain. KBS, KBE and expert systems are used in manufacturing knowledge domain structuring the knowledge using different techniques. In a similar manner AI based systems are different techniques in the KM to support decisions. The understanding of the knowledge types and its complex relationships within the significant volume generated has received significant attention from researchers in the creation of these systems. The manufacturing domain has had only limited work attempted concerning manufacturing knowledge models. This thesis made a contribution on manufacturing knowledge modelling providing good understanding in knowledge types and its relationships to support the long-term use of these systems.

Information and knowledge modelling is a fundamental requirement in the definition of decision support systems based on information/knowledge. Information modelling is identified as a useful approach to embody and supply significant information. For example: product and manufacturing models have proved to be an efficient manner for storing information related to the product and the facilities of an enterprise. The research on manufacturing model has advanced from station level to enterprise level. Manufacturing model research has included the domains of injection moulding processes and machining processes and in addition has explored applications for: a) design for manufacture and assembly, b) machining and assembly process planning. Much work has been done in information and knowledge modelling in recent years. Many of these works are concerned with product data modelling and manufacturing data modelling. However, there is no existing manufacturing model that can support manufacturing knowledge management and maintenance. This is the main motivation of this research.

According to the previous literature review research work related to manufacturing knowledge maintenance was not found (Guerra and Young 2002). Only general work related to knowledge maintenance using AI technology was found. However, knowledge maintenance using AI technology is out of the scope of this thesis.

Process planning is an engineering analysis for the purpose of selecting the correct method, machine, and tooling to produce machining parts (Bell and Young 1992). There is a lot of research work in process planning, however this thesis is focused on the creation of new knowledge structures to support manufacturing knowledge maintenance. Process planning is used simply as an example to demonstrate the applications of this research. Hence process planning literature has not been reviewed here.

CHAPTER 3

3. A NOVEL APPROACH TO MANUFACTURING KNOWLEDGE MAINTENANCE

3.1. Introduction

This chapter explains the author's research idea discussing how to define an information and knowledge structure to enable knowledge maintenance.

Two main sections are reported in this chapter. The first section discusses the issues of knowledge based decision support systems, arguing four critical points used to support the knowledge maintenance problem. The second section explains the author's research idea, describing a knowledge maintenance framework and detailing two main elements: a) the research issues relating to the development of a new Manufacturing Information and Knowledge Structure as a core part of this framework, b) a knowledge maintenance life cycle concept as a knowledge maintenance method to support maintenance of manufacturing knowledge. In addition to presenting a new knowledge structure, this chapter introduces the research idea with the main information and knowledge structures as well as their relationships. The detailed work that establishes these structures is reported in chapters 4 and 5.

3.2. Decision Support Systems Based on Knowledge

3.2.1. General Issues

As previously described in chapter 2, section 2.3, decision support systems research based on knowledge can be grouped into 3 areas: (a) Knowledge Based Systems (KBS) which are focused on how to capture, represent and apply knowledge about specialised areas; (b) Case Based Reasoning (CBR) which focus on how to represent, organise, select and adapt past cases in order to find a good solution to the actual given case; and (c) Knowledge Management Software Tools which are mainly focused on providing the user with a configurable tool to support engineering and business decisions.

Supporting manufacturing decisions using systems based on knowledge requires exploitation of information and knowledge structures. KBS are more compatible with the definition of information structures, giving better information and knowledge representation and making better use of object oriented databases (Costa 2000). This approach has the potential to provide a supporting structure for the complex relationships, which exist in manufacturing knowledge.

In recent years KBS have been used to support manufacturing and design decisions as important tools for obtaining a competitive advantage and leverage using what the company "knows". The product development process, within a typical manufacturing company, utilises large amounts of knowledge related to manufacturing and design activities. However, due to the significant volume of knowledge generated in the manufacturing and design stages, there is a need for an efficient and systematic approach to structure this knowledge. This will enable the knowledge to be readily maintained (Rezayat 2000); assuring the long-term use of these systems (Sainter et al. 2000).

Important elements in this thesis are consistent knowledge structures and methods that allow knowledge storage assuring the long-term use of KBS. This is in line with Sainter et al. (Sainter et al. 2000) and Rezayat (Rezayat 2000). They explored the relevance of these elements according to two different views. Sainter et al. (Sainter et al. 2000) identified the key role of knowledge management to obtain a suitable methodology and framework to allow the short term benefits of KBS to be extended to the long term. However, he did not explore the understanding of different types of knowledge classification. This is considered a critical point of focus in this thesis. Rezayat (Rezayat 2000) recognised the importance of knowledge maintenance in KBS to share large amounts of knowledge in a persistent manner. However, he did not report how the knowledge used can be structured and maintained. This is another critical point of focus in this thesis. These critical points can be resolved through the creation of consistent knowledge structures and methods that allow knowledge storage assuring the long-term use of KBS.

3.2.2. Information and Knowledge Modelling to Support Manufacturing Decisions

Significant advances have been made in Manufacturing Information Modelling (MIM) to support decisions throughout the product realisation process using the concepts of: (a) the Product Model; and (b) the Manufacturing Model. These models are mainly focused in the support of the decision making process. However, the need to develop flexible systems that can be readily maintained with up-to-date information still exists (Young 2003).

Many industrial and research groups have explored the concept of Knowledge Management as a tool for managing different types of knowledge, however the majority of the examples presented are related with business knowledge. For example, Smith (Smith 2001) proposed alternative techniques for recognizing, acquiring, sharing and measuring tacit and explicit knowledge that improves the understanding of the role of this knowledge in the workplace. However, he did not explore how this knowledge can be made available within a computerised application for an engineering domain. This requirement is a further important issue for this research.

As explained in chapter 1 the scope of this research is focused on machining knowledge to support process-planning decisions. An understanding of types of manufacturing knowledge including the classification and structures to simplify the process planning decision is necessary (Sormaz and Khoshnevis 1997). Although Sormaz and Khoshnevis (Sormaz and Khoshnevis 1997) emphasise the fact that different types of knowledge can support manufacturing process planning decisions, they do not explore how different types of knowledge representation can be used in a manufacturing knowledge structure. This is also a critical point for this research.

It has been identified, from the preceding literature survey, that three related issues must be solved to improve Knowledge Maintenance in KBS: (a) the inability to deal with various types of knowledge; (b) the capture of valuable new knowledge; (c) a method to be able to maintain knowledge. The approach taken in this thesis has provided a contribution to the solution of the knowledge maintenance problem. This followed from the consideration of the three related issues mentioned above and making particular emphasis in the following critical points summarised from sections 3.2.1 and 3.2.2

- Understanding how to classify types of manufacturing knowledge.
- Understanding what knowledge structures are needed to support manufacturing knowledge maintenance.
- How to apply manufacturing knowledge models to process planning.

3.3. Modelling manufacturing facility information and knowledge to support knowledge maintenance

A general explanation of the author's research idea addressing the problem of knowledge maintenance in KBS is presented in this section. The knowledge maintenance framework is shown in Figure 3-1 and related with Figure 3-2 and Figure 3-3, where the Manufacturing Information and Knowledge Structure and the Knowledge Maintenance Life Cycle are respectively depicted.

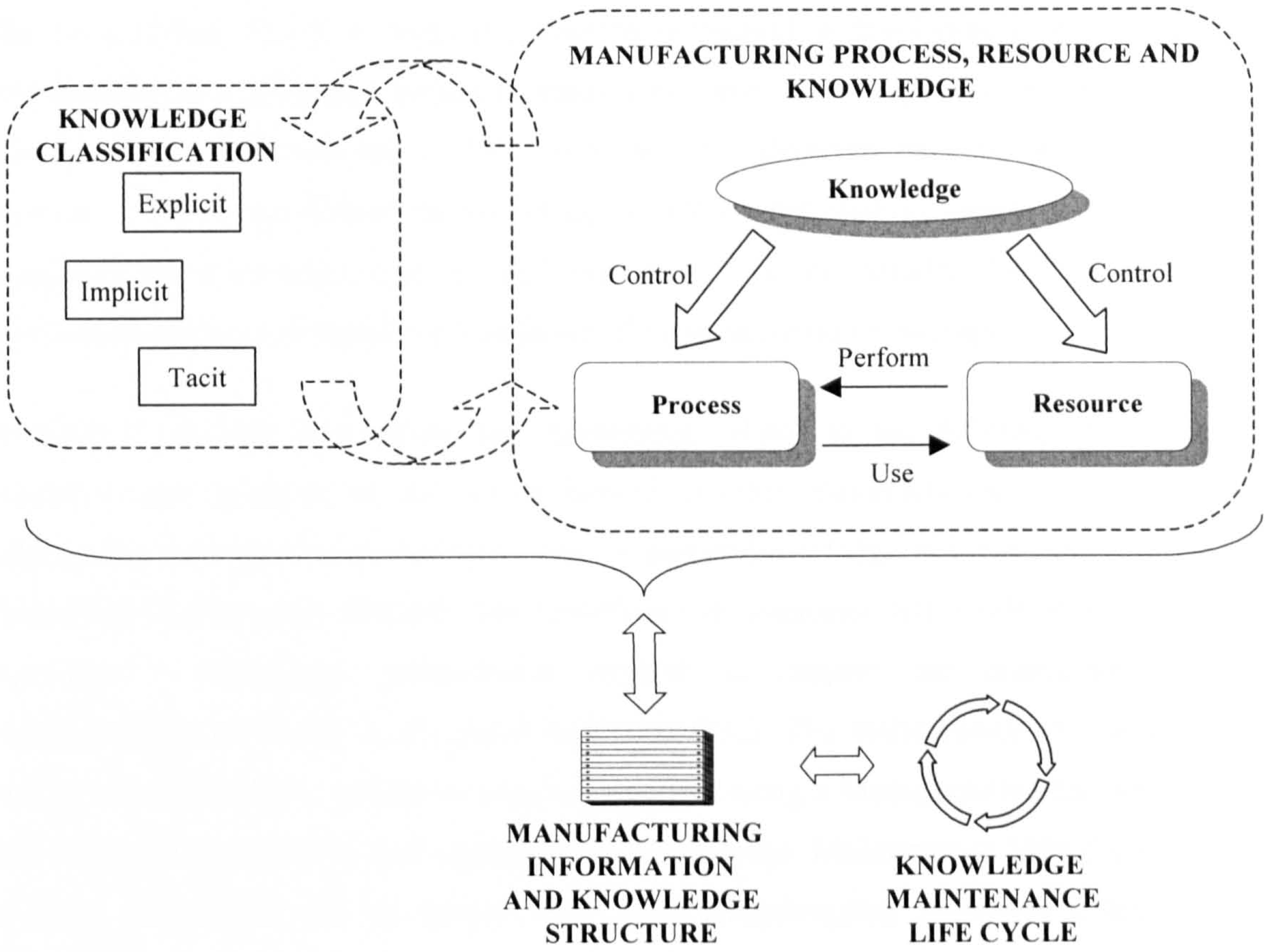


Figure 3-1. Knowledge maintenance framework

The author's research idea is applied within a manufacturing facility consisting of material removal processes to produce machined parts. The process and resource knowledge is structured to support machining process-planning decisions. Hence, knowledge to produce a machined part in a manufacturing facility using processes and resources at shop level is considered in the knowledge maintenance framework. The knowledge related to material removal processes and their resources is structured using explicit, tacit and implicit knowledge definitions.

The Manufacturing Information and Knowledge Structure considered in Figure 3-1 is a core part in the knowledge maintenance framework and it is needed to access the different types of knowledge related to process and resource. This structure allows the storage of machining information and knowledge into a Manufacturing Facility Information and Knowledge Model (MFIKM) and can be updated following a knowledge maintenance method. The top class level of the manufacturing information and knowledge structure is explained in section 3.3.1

The research described in the following chapters is focused on developing a new MFIKM emphasizing the difference between information and knowledge for processes and resources in a manufacturing facility. Thus, two key elements are considered: (a) the creation of a new manufacturing knowledge structure that enables improved access to manufacturing knowledge; and (b) the creation of a novel manufacturing knowledge maintenance method to support maintenance of manufacturing knowledge.

In order to identify and update new knowledge related to the different machining processes and resources as well as to expand to other manufacturing processes i.e. milling and turning, it is necessary to have a proper knowledge structure and apply a knowledge maintenance method. The knowledge maintenance life cycle concept that represents a knowledge maintenance method to support the maintenance of manufacturing knowledge is discussed in section 3.3.2. The maintenance of current as well as new information and knowledge is facilitated using a Manufacturing Information and Knowledge Structure and applying the Knowledge Maintenance Life Cycle. In addition, knowledge can be shared with other manufacturing processes using this approach.

3.3.1. Manufacturing Information and Knowledge Structure

Many industrial and research groups have developed the concept of a Manufacturing Model as a tool for managing manufacturing information (Al-Ashaab 1994), (Molina et al. 1995), (Harding 1996), (Zhao et al. 1999), (Molina and Bell 1999), (Giachetti 1999), (Dorador 2001). The work presented in this thesis extends Molina and Bell's (Molina and Bell 1999) approach with a significant contribution to knowledge structures. This then provides a basis from which to update the manufacturing knowledge by applying a knowledge maintenance method. Figure 3-2 shows a UML top-level class diagram, emphasising the area of the author contribution related to Molina and Bell's (Molina and Bell 1999) work which was detailed in chapter 2, section 2.4.4.

The research reported in this thesis has identified three main classifications in the new MFIKM to readily access and store the manufacturing information and knowledge and, as a consequence, allows their maintenance. These classifications are: (a) processes, (b) resources and (c) facility knowledge classifications. Although Molina and Bell (Molina and Bell 1999) proposed a process and resource classification, it was necessary to explore new processes and resources categorisations to enable knowledge maintenance according to the facility knowledge structure obtained. The definition of the structures for the new model is addressed in chapter 4.

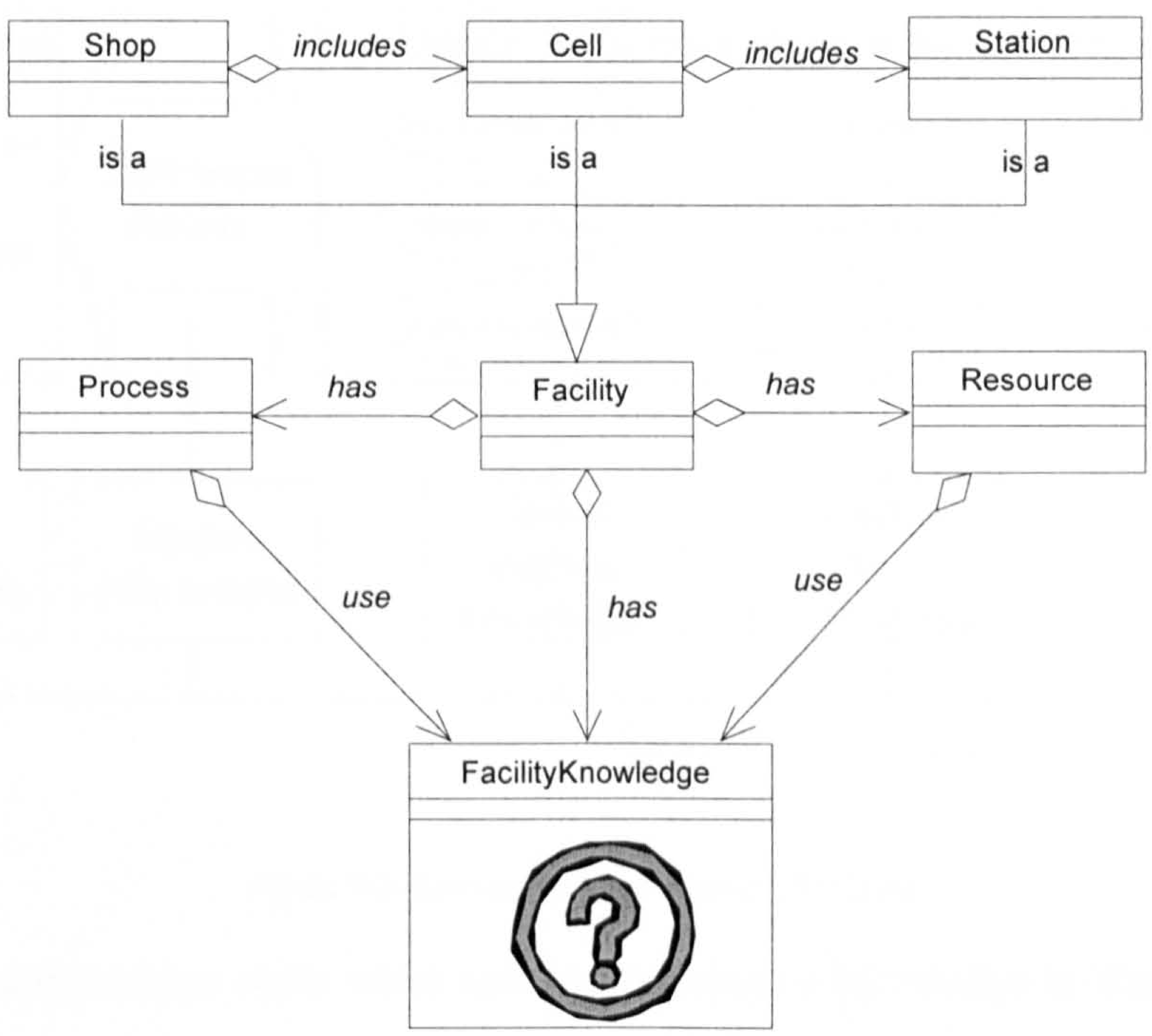


Figure 3-2. Manufacturing Information and Knowledge top-level structure.

Key relationships between information and knowledge related to processes and resources were additionally identified in a manufacturing facility, deploying and structuring the facility knowledge super class depicted in Figure 3-2. These information and knowledge relationships are explained in detail in chapter 5.

3.3.2. Knowledge Maintenance Life Cycle

The previous literature review indicates that no knowledge maintenance methods exist which are appropriated to provide a basis for this research. Hence, this section identifies the author's research idea in terms of a knowledge maintenance method that enables storage of up-to-date knowledge in the MFIKM. Although the title 'knowledge maintenance life cycle' emphasise only knowledge, this knowledge life cycle includes the up-to-date knowledge as well as the information stored into the MFIKM. Figure 3-3 depicts the knowledge maintenance life cycle identifying the main steps in order to make possible the information and knowledge maintenance contained in the manufacturing information and knowledge structure mentioned in section 3.3.1

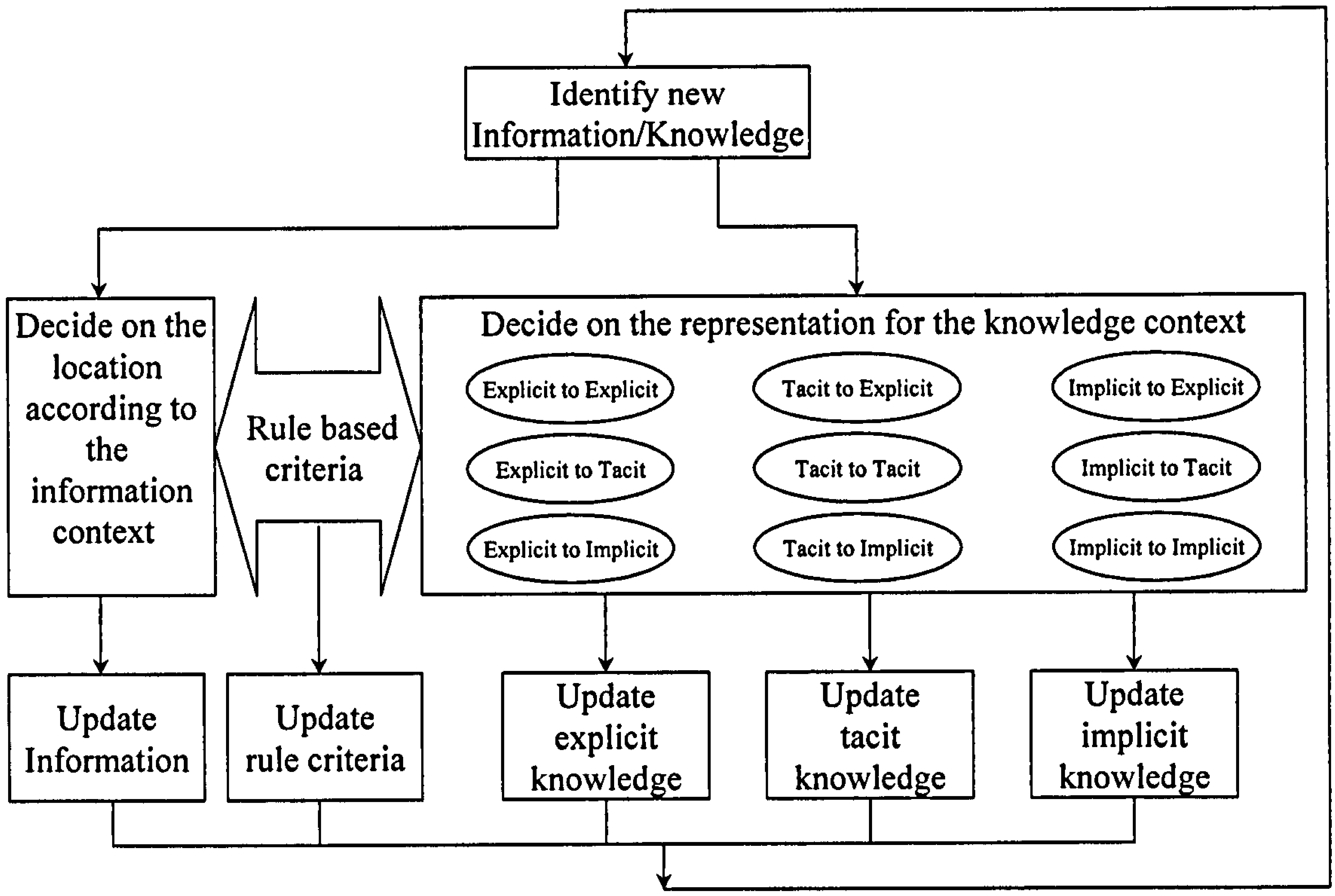


Figure 3-3. Knowledge Maintenance Life Cycle

Knowledge maintenance starts when new information or knowledge is identified. In the case of new information it is necessary to find the location of original information according to the MFIKM and then replace the old information with the new. This is also the case for new knowledge. In the case of new knowledge, the next step is to decide on its representation. This piece of new knowledge could be expressed in different explicit, tacit and implicit knowledge representations. The premise of this transformation is that the resulting knowledge should have "richer context" and provide better knowledge availability to make decisions by those who use it. The action to up-date the explicit, tacit and implicit knowledge is the way in which new knowledge is identified and added or substituted into the information and knowledge structure discussed in section 3.3.1. Sometimes, updating current explicit, tacit or implicit knowledge could be a change of data or a rule base criteria related to any knowledge representation, but in other cases it could be necessary to generate a new type of knowledge representation. Using this knowledge structure and applying the knowledge maintenance life cycle concept, it is possible to store and manage the creation of new knowledge. The information and knowledge stored in the MFIKM is updated using this knowledge maintenance method and explained in detail in chapter 6.

3.4. Summary

The research reported in this thesis argues that in order to obtain the knowledge maintenance in decisions support systems based on knowledge it is necessary to understand the different types of knowledge, exploring the best knowledge representation to access knowledge into a suitable knowledge structure. In addition it is necessary to define a method to support the maintenance of manufacturing knowledge.

This research proposes the hypothesis that a new Manufacturing Information and Knowledge Structure in combination with a knowledge maintenance method can provide good support for manufacturing decisions through up-to-date manufacturing knowledge.

There is a need for:

- The definition of a new manufacturing knowledge structure.
- The definition and implementation of key relationships between information and knowledge.
- The application of a knowledge maintenance life cycle.

CHAPTER 4

4. THE DEFINITION OF THE STRUCTURES FOR A MANUFACTURING FACILITY INFORMATION AND KNOWLEDGE MODEL (MFIKM)

4.1. Introduction

This chapter describes the range of information and knowledge available in a manufacturing facility, discusses the issues involved in modelling that information and knowledge and goes on to define the structure for the new Manufacturing Facility Information and Knowledge Model (MFIKM), which can be used in information and knowledge capture.

Three main sections are reported in this chapter. The general issues about information and knowledge in a manufacturing facility related to processes and resources and how the information and knowledge could be used to support process planning decisions are described in section 4.2. Manufacturing information structures in a manufacturing facility are explored in section 4.3, and manufacturing knowledge structures in a manufacturing facility are explored in section 4.4, emphasising how different types of knowledge can be used to represent processes and resources knowledge. This chapter also identifies the general relationships that must be captured by the MFIKM, and establishes a basis for the relationships which are presented in detail in chapter 5.

4.2. Information and knowledge in a manufacturing facility

4.2.1. Contextualisation of process and resource in a manufacturing facility

It is important to have an understanding of information and knowledge related to processes and resources in a manufacturing facility to explore the structures used in the MFIKM (Young et al. 2003). Figure 4-1 shows that a manufacturing facility has both processes and resources. Important differences were explored between information and knowledge related to processes and resources used to support manufacturing decisions. Comprehending the differences between information and knowledge related to processes and resources is important in knowledge structure definition.

The next paragraphs discuss issues related to the creation of information and knowledge structures. The focus of these structures is related to processes and resources in a manufacturing facility to support process planning decisions.

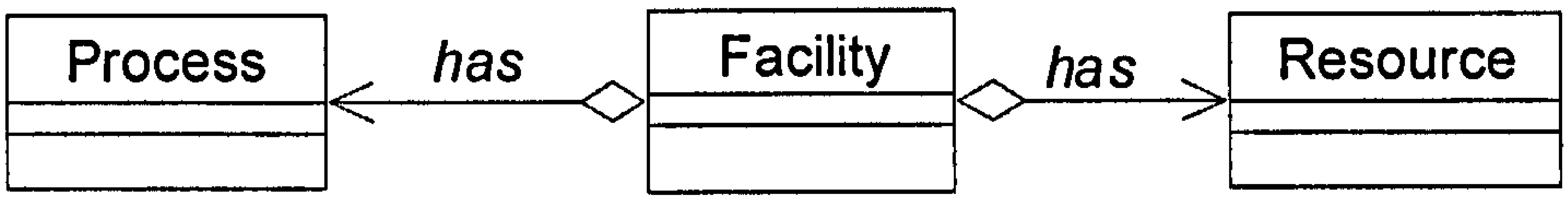


Figure 4-1 Facility information structure. Adapted from (Molina and Bell 1999)

There is a need to understand manufacturing knowledge interactions between information models and software applications in the creation of manufacturing information and knowledge structures. Manufacturing is a set of correlated operations and activities, which include product design, material selection, planning, production, inspection, management, and marketing of products, for the manufacturing industries (Chang et al. 1998). Process planning is the function of manufacturing that establishes which processes and parameters are to be used to convert a piece part from its initial form to a final form predetermined from an engineering drawing (Chang and Wysk 1985). The MFIKM structures capture the manufacturing information and knowledge related to processes and resources to support process planning decisions. Figure 4-2 illustrates the knowledge interactions between a manufacturing model and process planning applications.

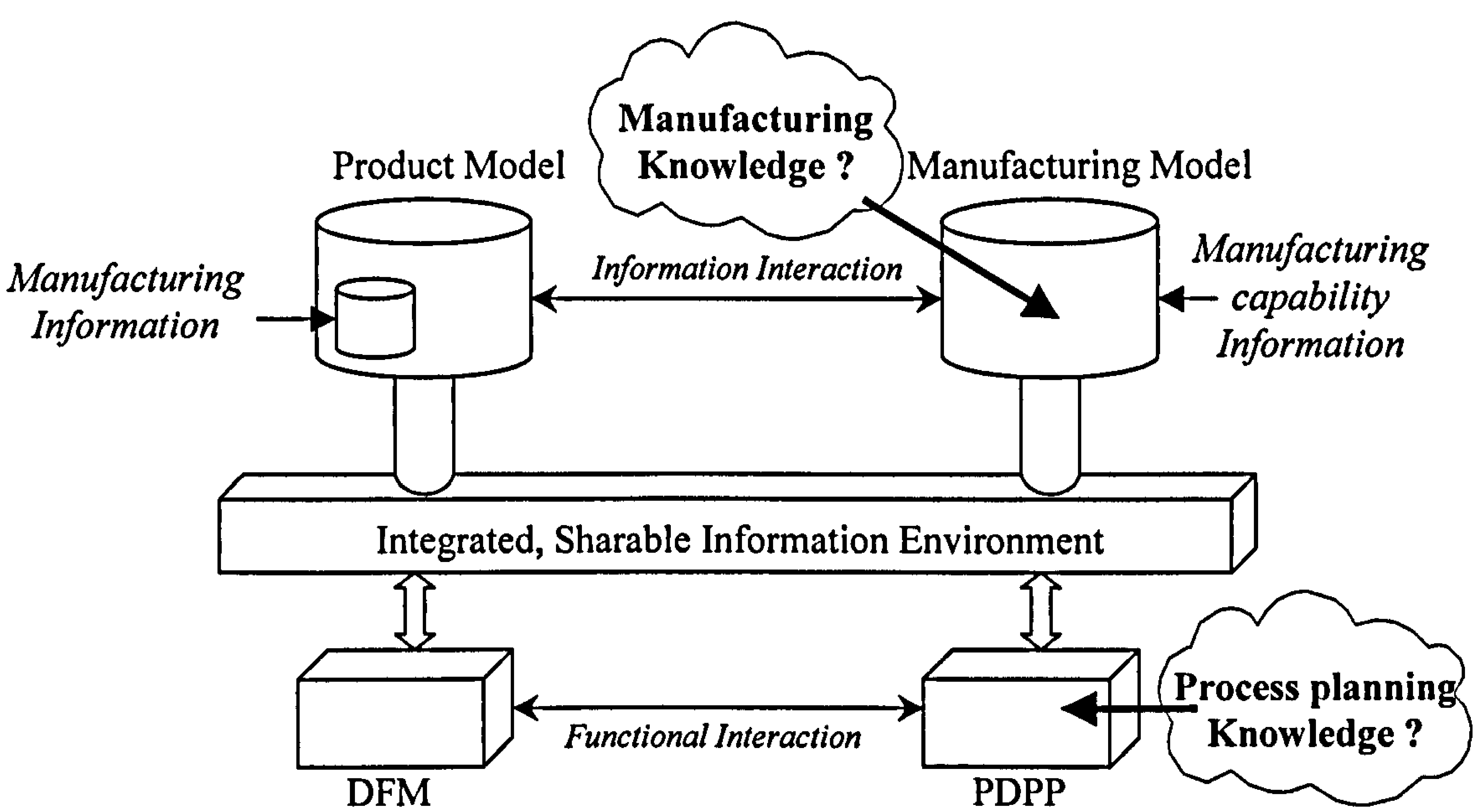


Figure 4-2 Knowledge interactions between information models and software applications (Zhao et al. 2000)

There is a need to understand more clearly the information and knowledge that relates to a particular subject within a manufacturing facility. For example the kind of information and knowledge about a twist drill and a drilling process required to support process planning decisions. This to define: a) processes information, b) resources information, and c) facility knowledge to be able to produce a manufactured part.

Two machined samples were analysed as examples to aid understanding of the organisation of knowledge in a manufacturing facility. The criterion for the samples selection was the complexity of manufacture according to two different machining shop's capabilities at Loughborough University. Figure 4-3 depicts sample I, a simple component which requires basic knowledge in order to produce a process plan. Figure 4-4 shows a more complex machined sample II that advanced knowledge is required to produce a process plan. These two machined examples were selected because it is possible to structure a wide variety of a) processes information, b) resources information, and c) facility knowledge to be able to produce the samples.

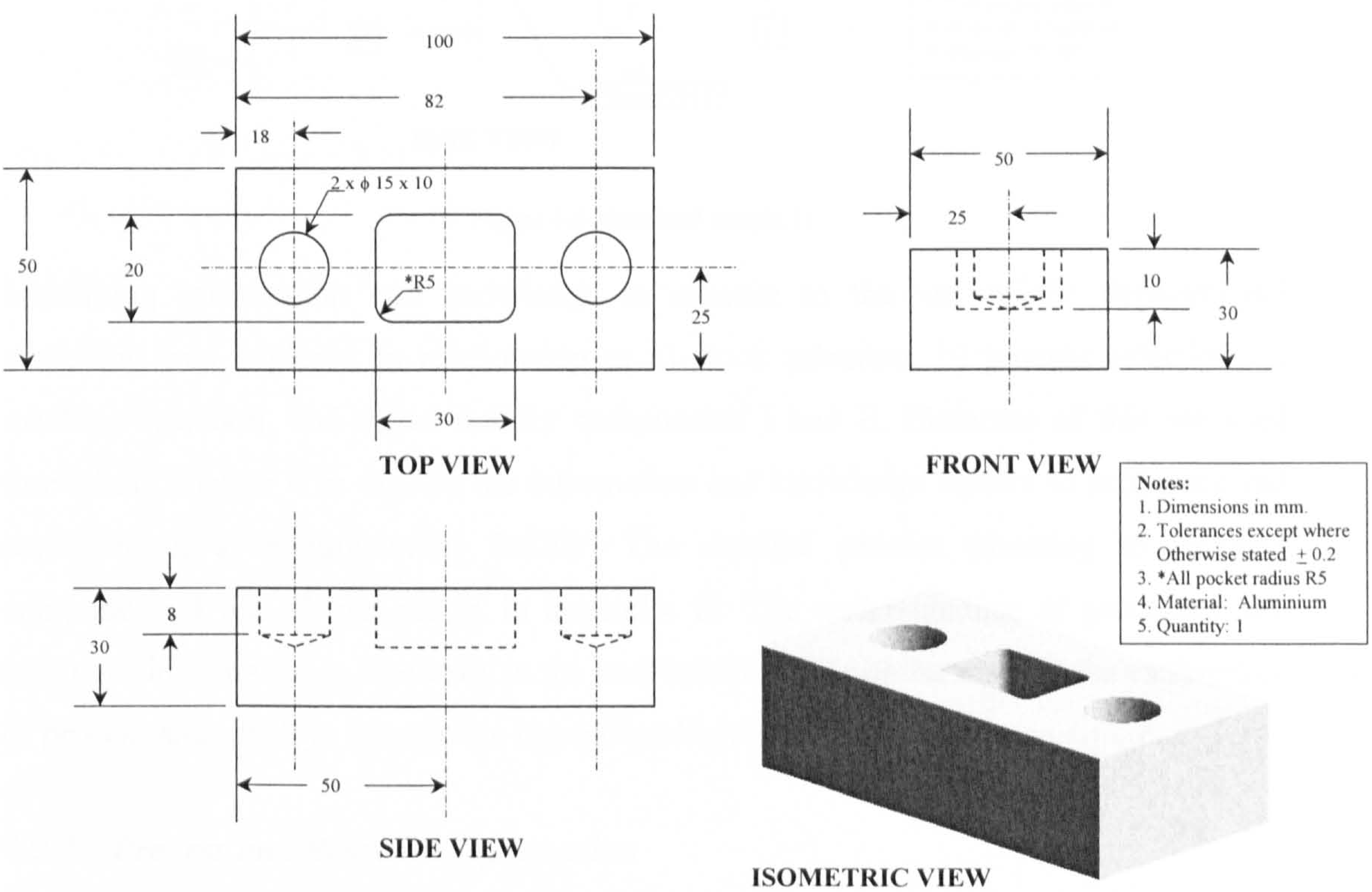


Figure 4-3 Machined sample I.

There are many different varieties of activities that are performed in a manufacturing facility resulting in complex information and knowledge structures related to processes and resources. For example: Figure 4-5 depicts some activities related to process planning decisions and gives an idea of the breadth of knowledge required to identify methods, processes and resources to be used for the manufacture of the machined parts depicted in Figure 4-3 and Figure 4-4.

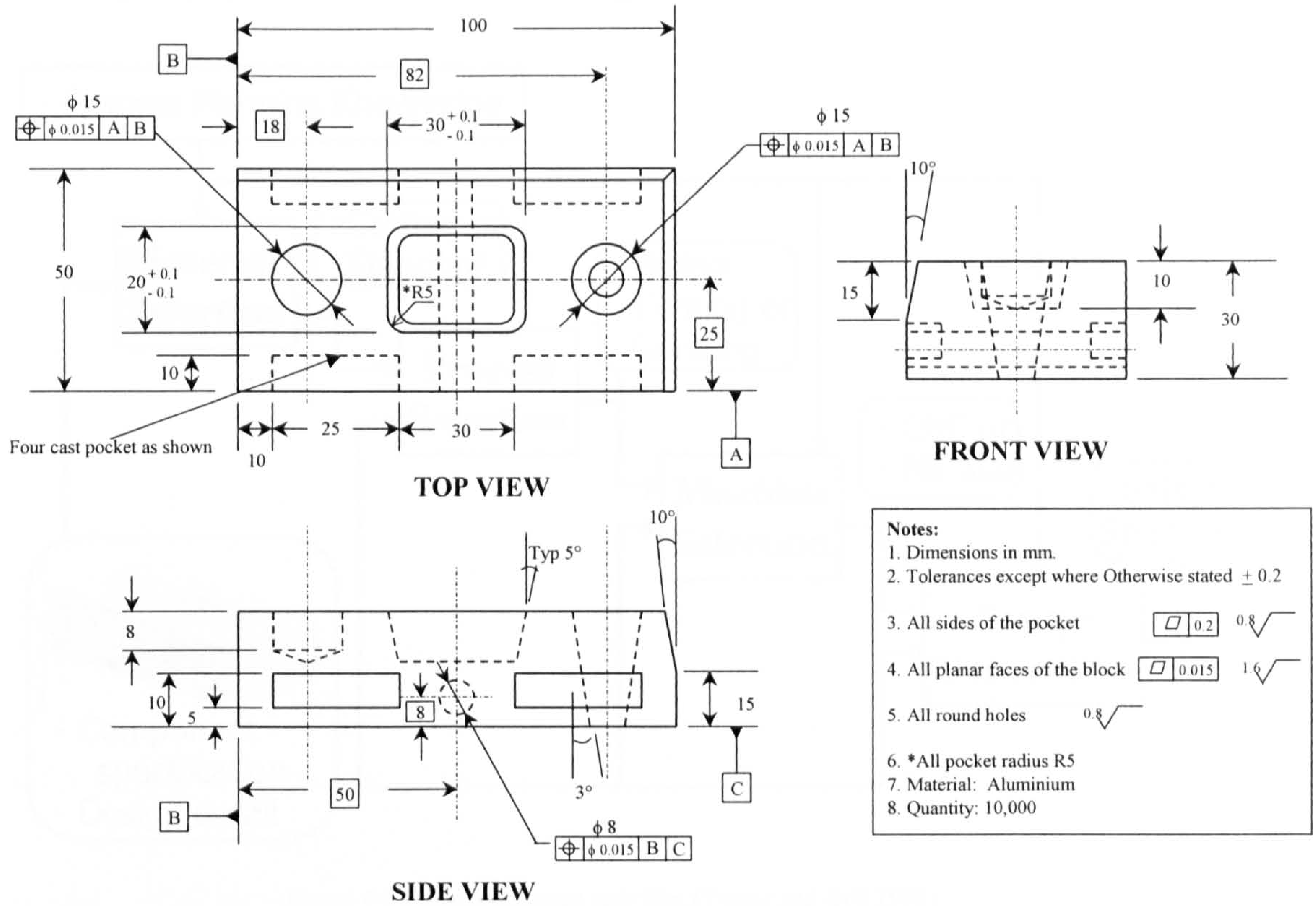


Figure 4-4 Machined sample II.

Machining information and knowledge in relation to the use of the departmental workshop was explored in relationship to a) stock selection, b) process selection, c) machine selection, and d) set-ups for components I and II. Elements of this are used throughout chapter 4 to explain the information and knowledge related to processes and resources in a manufacturing facility. The detailed process planning to produce components I and II are shown in appendix B. The understanding of processes and resources information is discussed in the next section. In a similar manner the exploration of process and resource knowledge is explained in section 4.2.3.

4.2.2. Process and Resource Information

It is not easy to identify what should be included as process information in a manufacturing facility and how it can be used to support decisions. Process information is the attributes about the process itself, including the process name, classification and description. For example, selecting the drilling process as a name, milling could be the process classification according to ISO/DIS 14649 –11 standard. The process description can be considered as follows: Drilling is the production of holes by the relative motion of a cutting tool to the work piece. The cutting tool moves forward cutting material and producing chips (Drozda and Wick 1983). Figure 4-6 shows the drilling process.

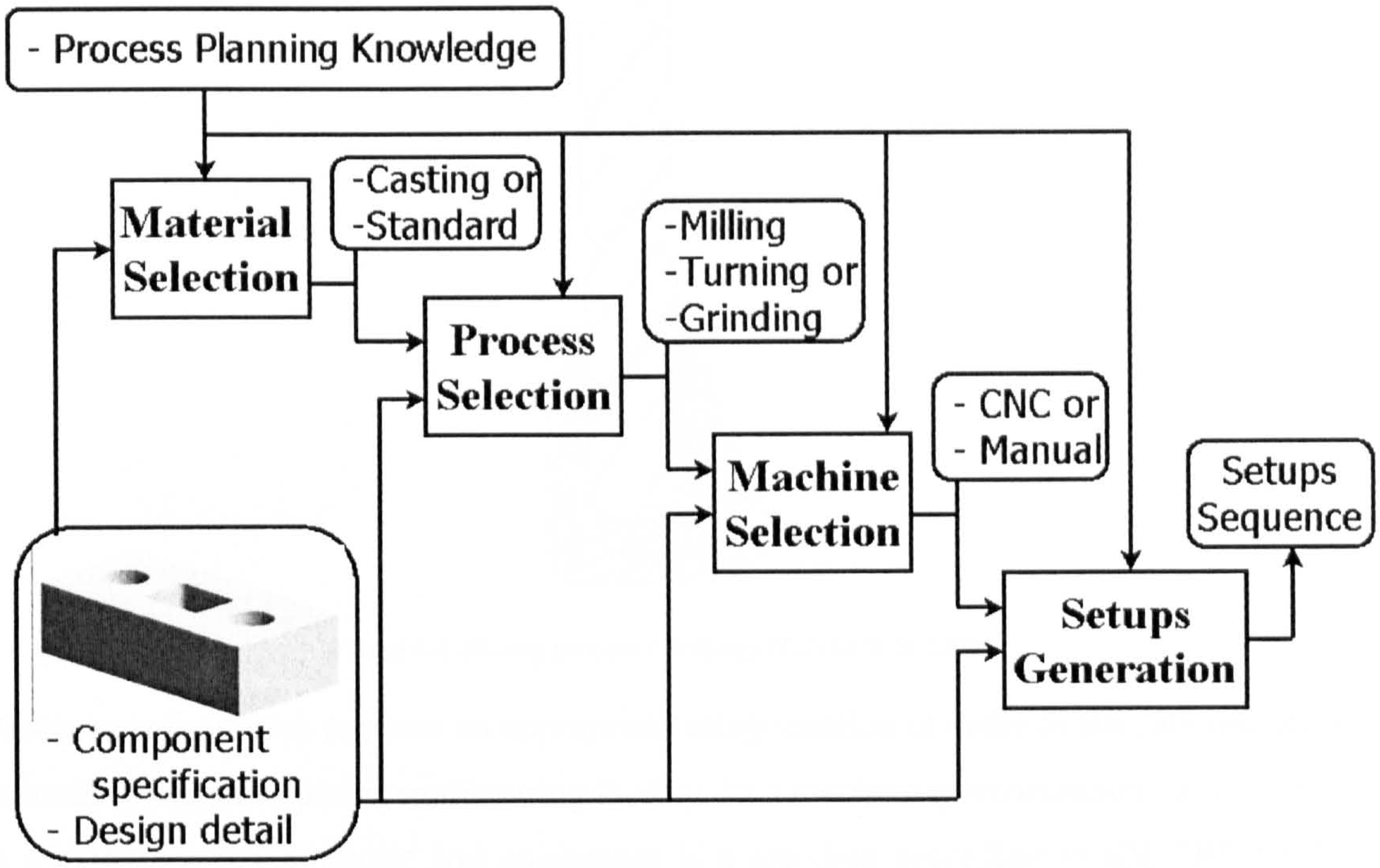


Figure 4-5 Process planning activities (Young and Bell 1992).

The kind of support that can be obtained in a manufacturing facility using the process information could be, for example, the identification of the current manufacturing processes and the attributes related to each process identified. In order to store and access the process description requires a suitable process categorisation in the manufacturing facility. The process categorisation used in this thesis is explained in section 4.3.2. From the manufacturing process information it is possible to gain a general understanding about the process itself. However, to know how each manufacturing process can be used to produce a manufactured feature is considered process knowledge and is explained in sections 4.2.3. The resource information in a manufacturing facility is explained in the next paragraph.

Resource information is structured data which uses different attributes to identify and describe a specific resource. A twist drill is considered as an example to explain the resource information in a manufacturing facility. Twist drills are not precision cutting tools, they have been designed to produce holes rapidly and economically (Oberg 1975). A general idea of the resource type can be obtained from the twist drill information depicted in Figure 4-7. However, resource knowledge is required to identify the appropriate twist drill and its parameters that are used to produce a particular hole. The resource knowledge is explained in sections 4.2.3.

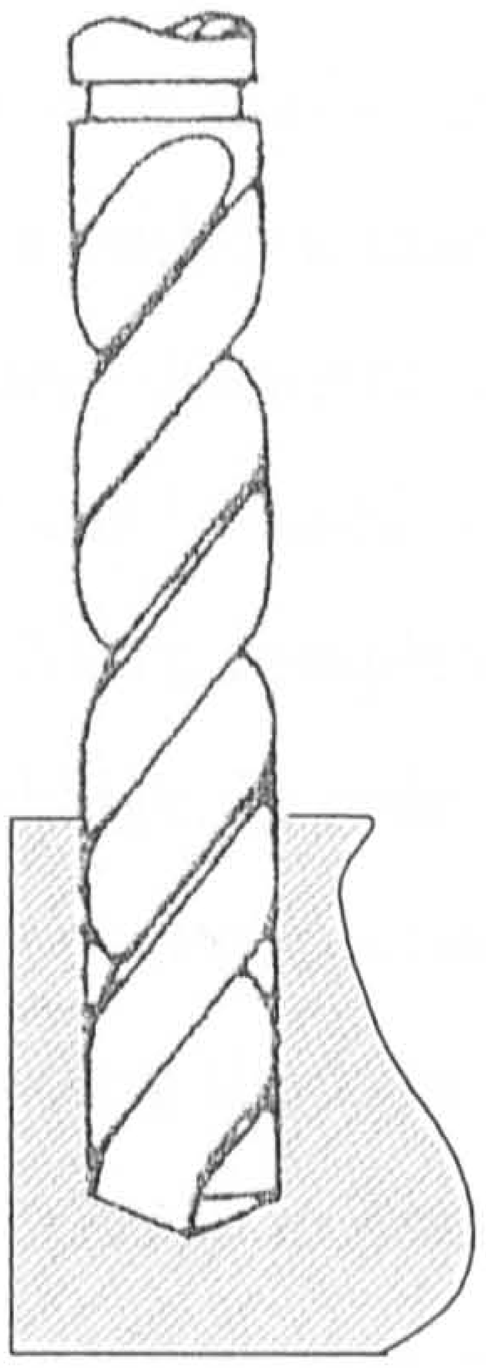


Figure 4-6 Milling process (Drilling) (TC184/SC4 2003).

Resource information requires an appropriate categorisation in order to allocate resources according to a particular manufacturing facility. In a machining environment, a twist drill is a tool, tool is equipment and equipment is a resource according to IEC/DIS 62264 standard. The resource information categorisation used in this research is explained in detail in section 4.3.3.

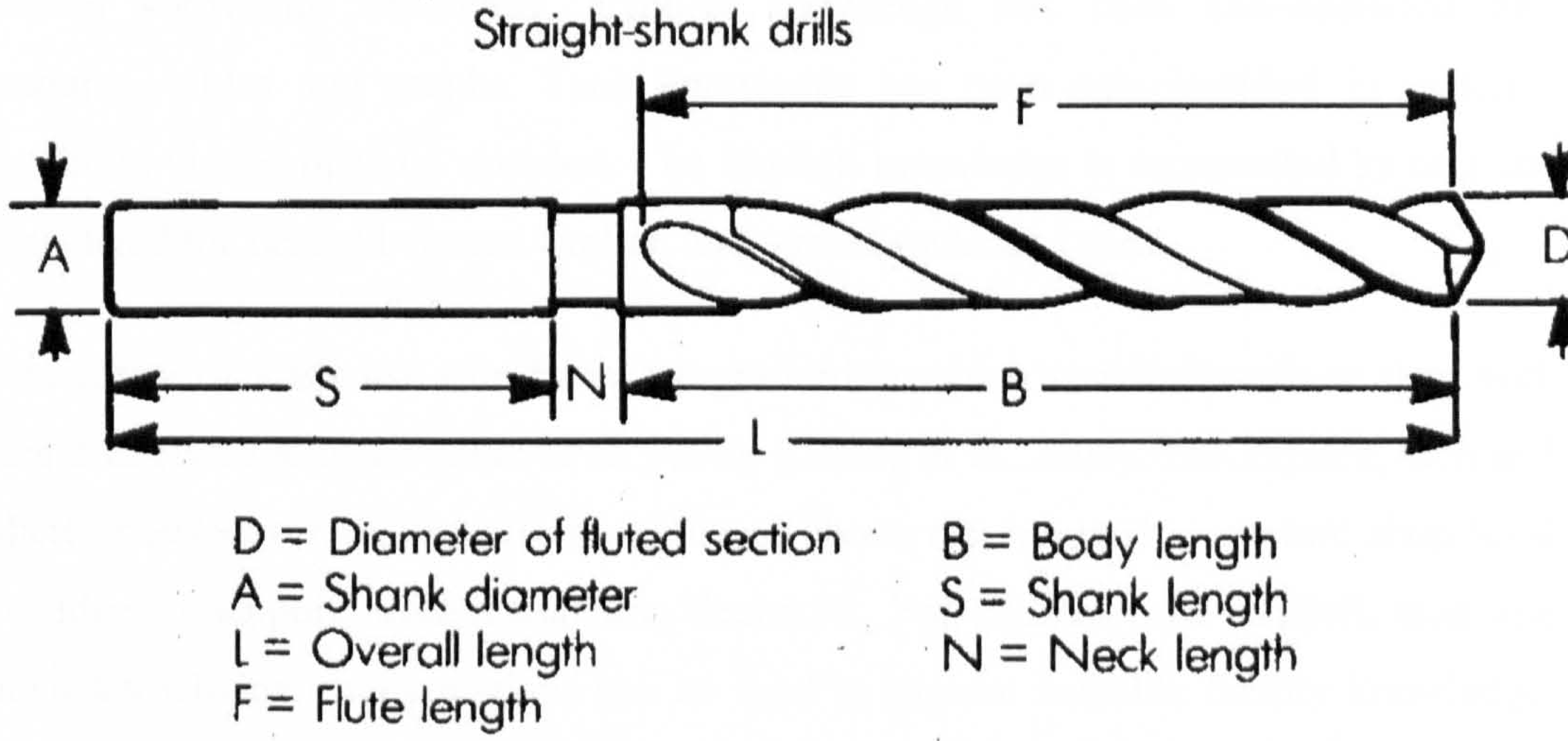


Figure 4-7 Twist drill detailed information (Oberg 1975)

It is necessary to identify specific differences between manufacturing information and knowledge as it may be used differently dependant on the activity in question. Manufacturing resources information in relation to a twist drill could be, for example, "resource quantity 3", "diameter 5 mm" and "flute length 52 mm". Further information required to define the use of the twist drill is considered knowledge. Organising the information attributes related to a particular resource it is possible to obtain useful manufacturing meaning (Shehab and Abdalla 2002). For example, identifying the number of 5 mm diameter twist drills within a manufacturing facility should be enough to combine the resource quantity and diameter information. However, to identify a suitable twist drill and explain how it can be used to produce a particular hole, more than the resource information is required. More complex holes such as tapered holes, counter bored holes, etc. require further knowledge. In order to suggest knowledge structures, it is important to emphasise differences between information and knowledge. Secondly, it is necessary to move towards understanding the type of knowledge as well as the relation with the users and the use of the knowledge to plan the production of produce a product (Mills and Goossenaerts 2001). The next section presents issues related to process and resource knowledge.

4.2.3. Process and Resource Knowledge

As previously discussed in chapter 2, section 2.2.3, several researchers have defined the different types of knowledge that humans use to make decisions. As a consequence, the machining knowledge types are classified as explicit, tacit and implicit. In addition, these knowledge types are further sub-classified to enable the representation of processes and resources knowledge structures. Explicit knowledge has been sub-classified into procedures, tables and graphs. Tacit knowledge has been sub-classified in patterns, storytelling, video clips and sketches. The implicit knowledge is represented by text and is considered the bridge between explicit and tacit knowledge types.

The majority of KBS use rule based programming which is not enough to deal with different knowledge types (Choi et al. 2000), (Chung et al. 2003). The explicit, tacit and implicit knowledge representations mentioned above can be used to capture shop level knowledge to support process planning decisions. For example: the explicit, tacit and implicit knowledge representations can be used to capture valuable facility knowledge, which is not included within most of the KBS.

There is a need to understand the association between the facility knowledge and the facility information relating to processes and resources. Figure 4-8 represents the association of the facility knowledge and the facility information relating to processes and resources. By analysing the diversity of resources and processes in a manufacturing facility, it can be established that there is a lot of facility knowledge relating to different subjects at different levels of detail. The first issue is to identify what we know about processes and resources and secondly how the knowledge structure can be defined.

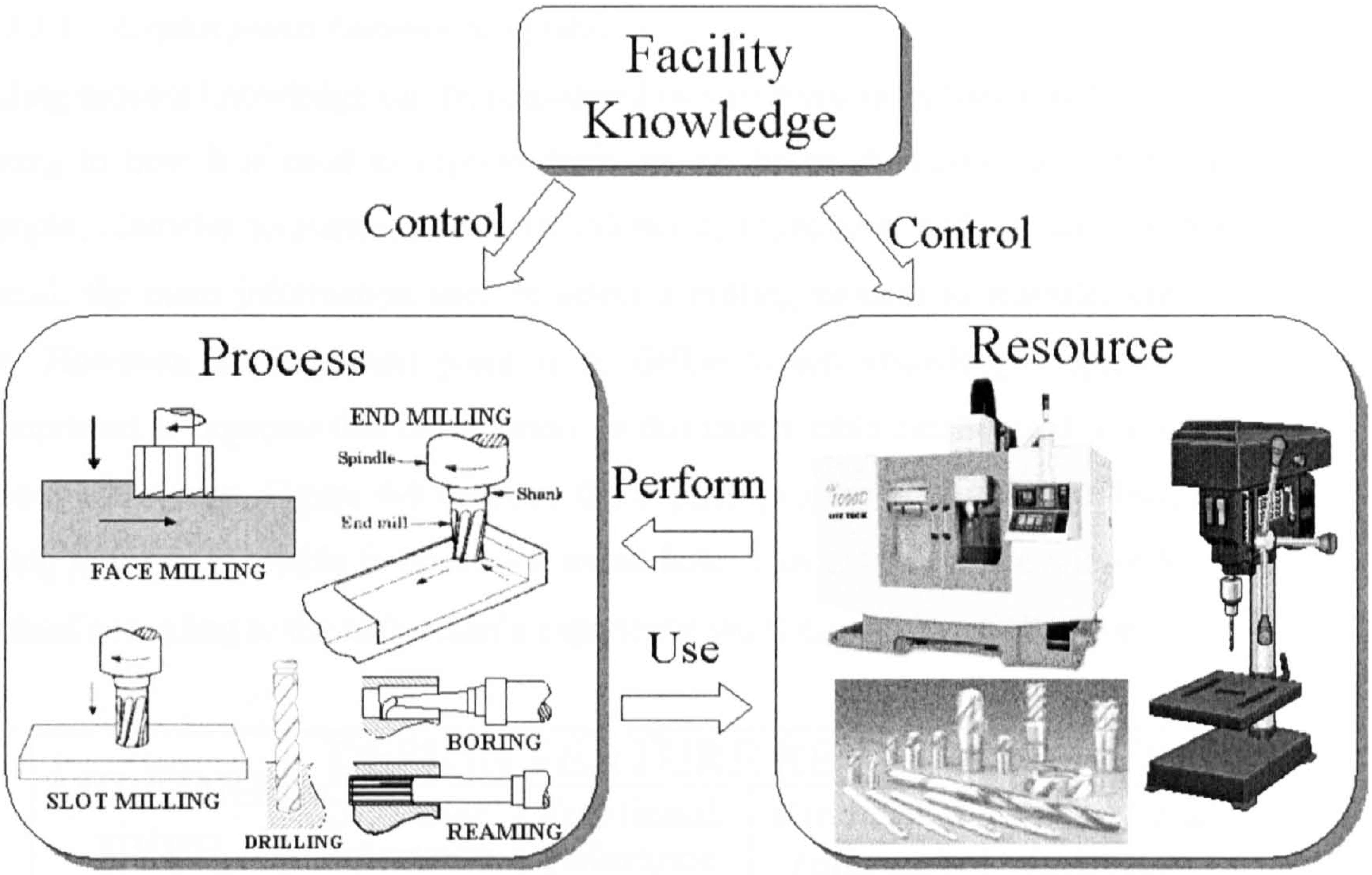


Figure 4-8 Facility knowledge, process and resource relationships

Facility knowledge is an important part in the knowledge Model obtained because it contains all the process and resource knowledge identified in the manufacturing facility. Therefore, it is necessary to define a structure that allows the access and storage of the wide range of facility knowledge. The processes and resources knowledge structures obtained are presented in section 4.4. However, to explain these structures it is necessary to explain what processes and resource knowledge is in the manufacturing facility and how it can be represented. A series of process knowledge examples are illustrated in section 4.2.3.1, as well as resource knowledge examples are shown in section 4.2.3.2.

4.2.3.1 Process Knowledge

Knowledge related to manufacturing processes has been structured using the different types of knowledge representations mentioned above. The process knowledge presented was structured to support process planning decisions for the samples I and II depicted respectively in Figure 4-3 and Figure 4-4. However, the knowledge represented in this section is mainly to support the hole making process. Through these representations, the author shows a wide range of process knowledge that technicians use in a variety of manners to produce a hole. In the next paragraphs explicit process knowledge using tables, procedures and graphs are presented, secondly tacit knowledge using video clips, sketches, patterns and story telling are explained. Examples using implicit knowledge type are presented at the end of this section.

4.2.3.1.1 Explicit process knowledge using tables

Drilling process knowledge can be considered as structured information with added detail relating to how it is used to support decisions in the production of a round hole. For example, diameter tolerance, positional tolerance, roundness, and surface finish are, in general, the main information used to select a milling process to manufacture a round hole. However, an important point is to define which knowledge representation is appropriated to organise this information. In this case a table can be used to organise the process knowledge. Figure 4-9 contains the explicit process knowledge to decide which milling process is suitable to produce a round hole. This explicit process knowledge was obtained according to the technician's experience working within a CNC shop.

MILLING TYPE PROCESS	DESIGN FEATURE REQUIREMENTS							
	Diameter Tolerance (mm)		Positional Tolerance (mm)		Roundness (micron)		Roughness (micron)	
	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.
DRILLING	0.020	0.250	0.020	0.250	50	100	1.6	6.3
REAMING	0.005	0.020	0.010	0.020	25	50	0.8	1.6
BORING	0.005	0.010	0.005	0.010	15	25	0.4	0.8

Figure 4-9 Table explicit knowledge representation to select a milling process.

The experience gained by the technicians to solve manufacturing problems can also be considered to be process knowledge. Generally the greater the experience held by a technician the greater the knowledge they possess. A table explicit knowledge representation can be used to capture process knowledge to solve drilling process problems. Figure 4-10 describes some of the common problems found during drilling operations. Organising the process knowledge in a table explicit knowledge representation is important because can be capturing the right knowledge in the right format avoiding valuable knowledge loss (Rezayat 2000), (Kreiner 2002).

The drilling problems captured in Figure 4-10 can appear in the manufacture of a round hole. Some recommendations are defined and could help solve the drilling problems and be extended by other types of knowledge representations such as procedures, storytelling, video clips, etc. This example shows how the technician's knowledge gained by their work experience can be structured in order to develop a solution for drilling problems. This representation can equally be applied to other manufacturing problems or be applied to new technology knowledge.

DRILLING PROBLEM	POSSIBLE CAUSE	MANUFACTURING TROUBLESHOOTING			RECOMENDATIONS		
		MACHINE	TOOLING	PART	DESIGN	MANUFACTURING	NEW TECHNOLOGY
•EXCESSIVE BURRING •BUILT UP EDGE FORMING	•DRILL POINT GEOMETRY		- Geometry of Drill point	- Drill point geometry versus type of material	- Specify in the product design a drill point geometry.	- Specify the drill point geometry in the maintenance procedure. - Redefine the drill point geometry according to material.	- Ultrasonically assisted drilling in aluminium alloys can help to reduce, and under some conditions, completely eliminate the problem of burring. (This is a research Concept.)
	•SPEED AND FEED	- Machine settings			- Specify in the product design the suitable speed and feed.	- Redefine machine settings according to specific case. Consult Graph EK001	
	•SHARPNESS OF DRILL •DRILL WEAR		- Cutting edge angles.			- Redefine the drill sharpness.	
	•COOLANT	- Cooling concentration and pressure		- Type of cooling versus type of material.	- Specify in the product design the suitable coolant to the machining operation	- Redefine the cooling concentration and pressure. - Consult Storytelling TK001	
•EXCESSIVE VIBRATION	•DIFFERENT CAUSES RELATED TO MACHINE, TOOLING AND PART	- Worn bearings. - Slide wide - Machine drive. -Machine installation - Pillar drills table lock	- Drill point geometry. - Length of the tool. - Speed and feed. - Tool holding.	- Clamping system -Variable part structure. (Variation in the part cross section)	- Specify in the product design a) A drill point geometry. b) Speed and feed c) Maximum tool length.	- Review the machine troubleshooting according to the maintenance procedure - Redefine the tool holding and clamping systems.	

Figure 4-10 Explicit knowledge to solve milling problems drilling a round hole

4.2.3.1.2 *Explicit process knowledge using procedures*

Drilling, reaming and boring are milling type processes that can be performed using different procedures. Considering the two machining samples, a general procedure to drill a round hole is defined in the next paragraph. It is considered that the operator uses the work piece design information and the manufacturing capabilities to determine the machine to be used. The next procedure is an example of a hole drilling defined by the technicians. The main steps shown below should be followed to produce a successful drilled hole. Additional knowledge representations (i.e. procedures, sketches, etc) are connected with the main procedure, linking the initial piece of knowledge with other knowledge types to support decisions at different levels of detail. The general procedure was obtained with the assistance of the technician in order to help novice operators attain the knowledge representations to support decisions required for drill holes.

1. Load the work-piece. See procedure P002.
2. Secure the work-piece. See sketch SK001.
3. Locate position for drilling. See pattern PT001.
4. Define tool specification. Use graph G001.
5. Load the tools. See procedure P003.

6. Define speeds and feeds specification. Use graphs G002, and G003.
7. Define coolant or lubricant specification. Use table T002.
8. Define and load centre drill specification. Use Procedure P004 and Table T003.
9. Produce the centre drill hole. See video clip VC001.
10. Produce the drilled hole. Pre conditions: If the diameter is less that 15mm drill to size, if the diameter is higher that 15mm drill a hole or holes to leave 2 mm wall thickness before the last drilling. See Procedure P005 and video clip VC 002. Post conditions: If during the drilling process some machining problems appear. See Table T004 and See story telling ST001
11. Remove tools. See procedure P006.
12. Unload work. See procedure P007.
13. Critical analysis and feedback.

Procedure P002, sketch SK001, etc, are examples to show how to explain a procedure step at different level of detail. Some of these knowledge representations are presented through this chapter.

4.2.3.1.3 Explicit process knowledge using graphs

Different methods can be used to determine the spindle speed to drill a hole. For example, Figure 4-11 organises explicit knowledge using a graph type of knowledge representation indicating recommended R.P.M. (revolutions per minute) for various materials. This knowledge was obtained as a result of previous experience, drilling different types of materials. These values are only recommendations and should be adjusted according to the working conditions and properties of the material being worked (Titext 2003). Some operators use a formula to determine the spindle speed instead of the graph depicted in Figure 4-11. For example $N = 12 * V / (3.142 * D)$, where N is the spindle in revolutions per minute, V is the cutting speed in feet per minute (obtained from tables), and D is the twist drill diameter (Oberg 1975). It can be observed that there are different methods to determine the spindle speed according to hole accuracy and technicians' experience. However, an important issue is to determine the best structure to access this knowledge in a database and how to keep it updated without losing valuable knowledge.

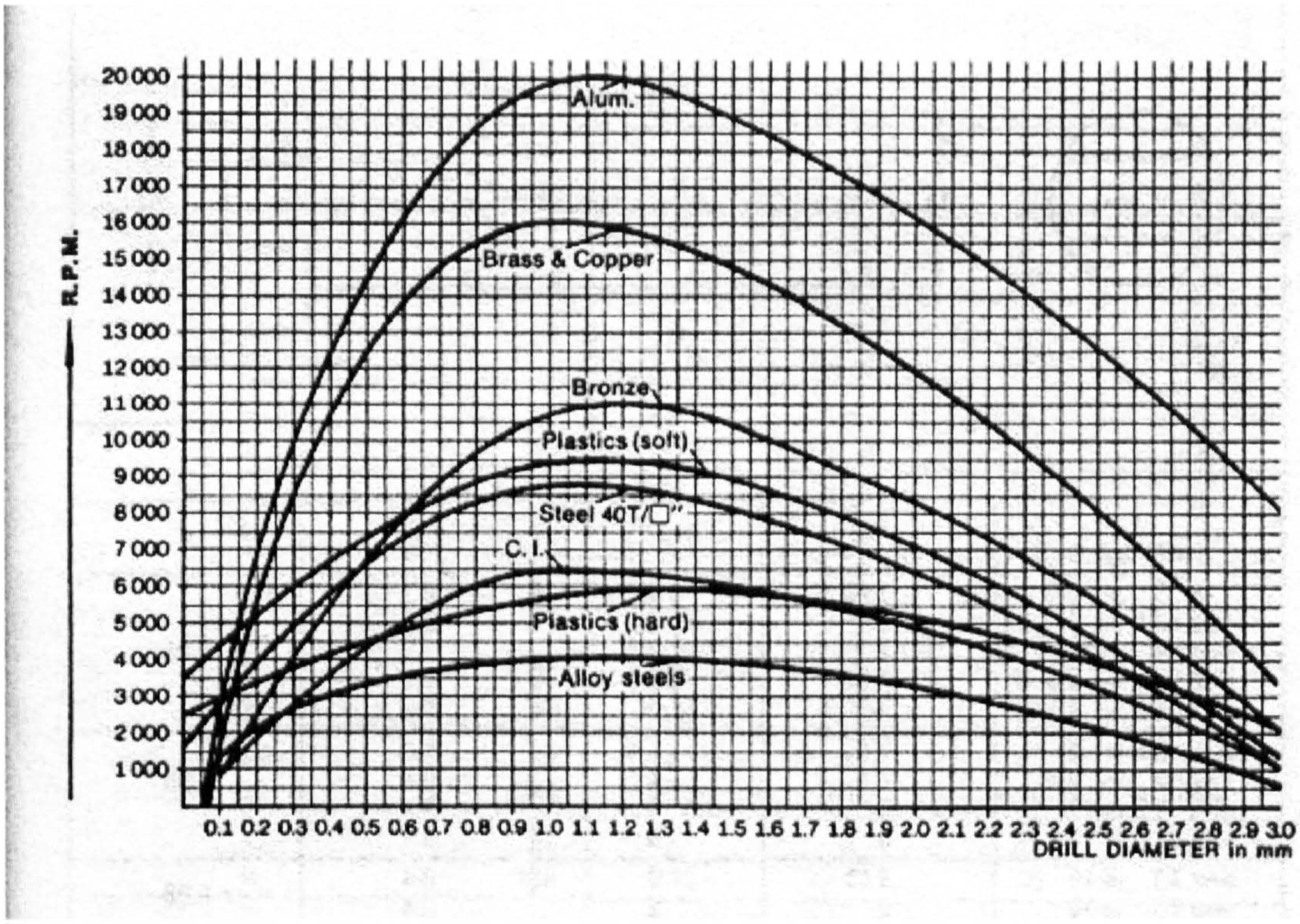


Figure 4-11 Recommended R.P.M. for small size drills (Titext 2003)

4.2.3.1.4 Tacit process knowledge using video clips

Tacit process knowledge can be considered to be the explanation of the best component set-ups in engineering terms, with a clear understanding between work-piece geometry, features accuracy, work holding methods, speeds, feeds, temperature in tooling or the cooling system (refrigerant), vibration in tooling or the work-piece, etc. This kind of knowledge is when the technicians might be saying the common phrase "I know how to do this but I can't explain it" (Nonaka and Takeuchi 1995). For these people it is extremely difficult to organise the know-how using the explicit representations mentioned above. It is necessary to work with knowledge elicitation and tacit knowledge representation techniques to obtain new knowledge availability. In the next paragraphs tacit process knowledge is structured using the same machining examples depicted respectively in Figure 4-3 and Figure 4-4.

Boring is considering a high accuracy milling process to produce a round hole and sometimes it is difficult to structure know-how related to the component set-ups. It is possible to access process tacit knowledge using video clips, avoiding valuable knowledge loss. Figure 4-12 depicts the representation of a video clip showing the component set-ups to bore a round hole.

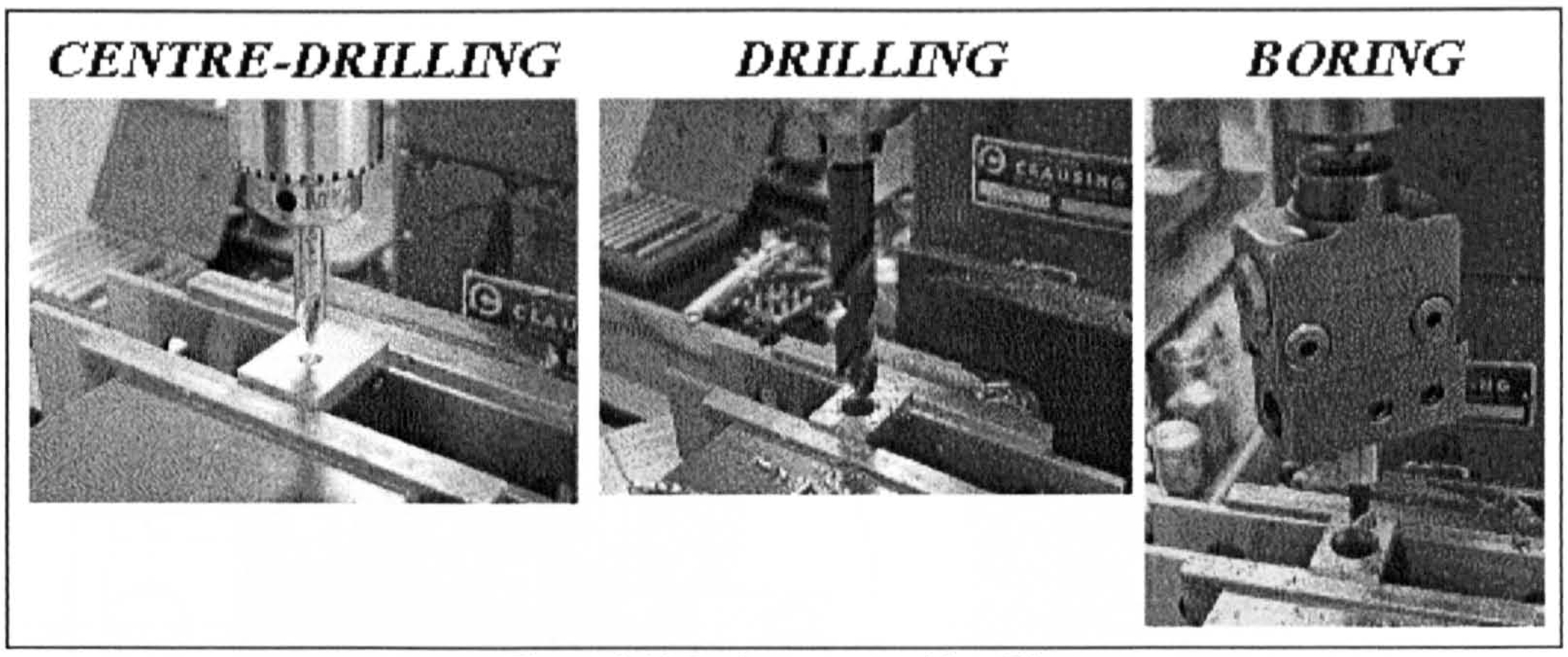
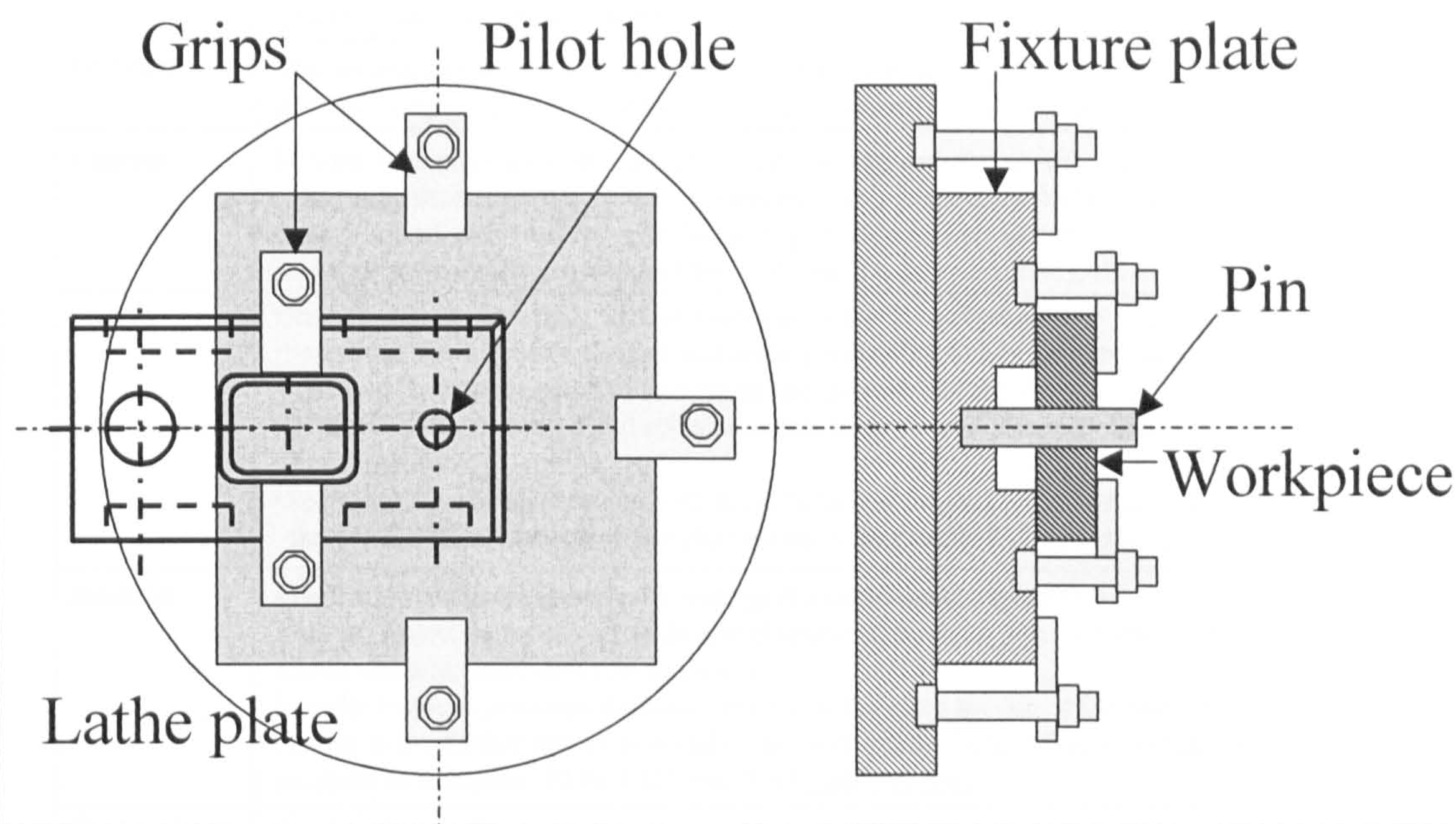


Figure 4-12 Boring process video Clip

4.2.3.1.5 Tacit process knowledge using sketches

The nature and complexity of engineering knowledge requires knowledge representation schemas to be as flexible and robust as possible (Sormaz and Khoshnevis 1997), (Gorti et al. 1998). Since there is no unique means of producing a manufacturing feature, the process knowledge should be organised in a proper manner to enable the technicians to reproduce the task. The tapered hole presented in Figure 4-4, sample II, requires a specialised task to produce this feature, because it is advisable to create a dedicated fixture to obtain the accuracy and amount of work-pieces required. Figure 4-13 depicts the sketch and the procedure to support the set-up instruction to produce a pilot hole and produce the tapered hole using a lathe. This tacit knowledge was obtained according to the technician's know-how working within a manual shop.

Sketch



Procedure

1. Locate fixture plate on lathe plate using grips.
2. Align fixture plate at lathe centre line according to pilot hole using dial indicator.
3. Locate workpiece on fixture plate using grips and pin.
4. Remove pin and turn tapered hole
5. Turn next workpiece repeating from step 3.

Figure 4-13 Sketch knowledge representation

4.2.3.1.6 *Tacit process knowledge using patterns*

Through time the engineering knowledge has been expressed in an explicit manner to be used by a decision support system based on knowledge. However trying to capture the tacit knowledge in an explicit manner is not the best method to do so because the essence of the knowledge can be lost, to avoid this, video clips, sketch, patterns, and story telling are being used (Ackerman 2000; Malhotra 2000). Continuing with the machining example, Figure 4-14 depicts a pattern to produce tight tolerance holes using a jig-boring machine. This tacit knowledge was obtained according to the technician's know-how working within a manual and a CNC shop.

Pattern Name	Machining tight tolerance holes using jig boring machine
Pattern Intent	This pattern addresses how to use operator skills to manufacture accurately guided plates on the Jig Boring Machine.
Problem	The technicians have problems with machining tight tolerances holes related to accurate settings, clamping, stress relieve and geometry distortion issues.
Context	In order to explore the entire assembly, the operator most be qualified and adaptable at any tolerance required. To take advantage of this pattern, the technician should have at least 5 year working with Jig Boring Machines. This pattern is most applicable in the cases when the geometry of the work-piece is complicate to hold it.
Forces	•Review that the clamping system works properly. Procedure CN009 *(Intranet link)* •Select the feeds, speeds, cooling and tooling according to type of material. •Analyse the whole assembly, tolerances and geometry of the work-piece. •Establish part orientation and references according to final assembly and functionality. •Sequence the operation in line with the structure of the part for example, variation of the cross section of the part. See pictures according to file F12 *(Intranet link)*
Solution	Concentrate on keeping accuracy settings related to the clamping system. Remove material properly according to diameter of the hole. For example, to machine 25mm diameter hole, drill first to 24 mm. In order to avoid geometry distortion related to the cross section of the material put the clamps in the thicker part of material in the work-piece. Take the next manufactured products as reference. P110, P123 and P145 *(Intranet link)*
Rationale	Good understanding in the accuracy settings and clamping techniques is important to manufacture accuracy parts in the Jig Boring Machine. It is necessary use clamps to hold the work-piece properly in order to avoid geometry distortions. The reason is that differences between the cross section in the work-piece and the clamp system should be subtracted the machining forces.
Resulting context	Keeping the accuracy setting, removing material and using clamping system properly can reduce the geometry distortion in a wok-piece when a Jig Boring Machine is used. This patterns is considering that the feeds, speeds, cooling and tooling are correctly selected according to the structure of the part being machined. It is important to emphasise that some machining operations need to be done without standard tooling and the skill of the operator needs to resolve the problem in these cases other patterns need to be constructed.

Figure 4-14 Pattern tacit knowledge representation

Explicit and tacit knowledge can be used in a different manner to support process planning decisions. It can be observed from Figure 4-11 that a specific answer is obtained each time that the graph is consulted to confirm a value, there is a R.P.M value recommended per each twist drill diameter related to a particular piecework material. However using the pattern tacit knowledge representation depicted in Figure 4-14 different useful ideas can be obtained to produce tight tolerance holes using a jig-boring machine. The combination of text explanation and format provide valuable tacit knowledge representation and provide wider knowledge context to support machining decisions.

4.2.3.1.7 Tacit process knowledge using story telling

In the next paragraph story telling is presented as an example of tacit knowledge representation of the technician's know-how about drilling holes using different materials.

Story telling title: Useful ideas to reduce burring problems producing a hole in aluminium.

Story telling context: Last June 2000 excessive burring occurred trying to produce a hole (8 mm +, - 0.1mm diameter and 25 mm length). All the conditions were according to current procedures and handbooks. The problem was reduced by 20% by using paraffin as a lubricant.

Story telling and patterns provide different layout to store process knowledge and how to use it depends on each particular case. Story telling could be suitable to use when the know-how could be transferred in a text manner with out too much detail such as telling a story (Swap et al. 2001). Personal notes related to day-to-day problems can be useful to write in order to identify the main problem and how it was solved using story telling. On the other hand, patterns provide more knowledge context related to a particular problem. For example different story telling can be used to produce a pattern. Though story telling and patterns have different methods to store technician experience, both can be used to store tacit knowledge and support machining decisions.

4.2.3.1.8 Implicit process knowledge

As previously described in chapter 2, section 2.2.3, several researchers have obtained different definitions about the implicit knowledge that humans use to make decisions. Nevertheless, in this research implicit knowledge has been used as a bridge between explicit and tacit knowledge to explore how it can be used to support manufacturing decisions (Zheng et al. 2001). There are, for example, different experiences applied to produce a round hole where implicit knowledge is used to organise explicit and tacit knowledge. For example, milling knowledge is the know-how of the drilling process performed in a milling machine. On the other hand, turning knowledge is know-how of the drilling process but performed in a lathe. However, the experience gained in turning knowledge can be applied to structure milling knowledge. The new techniques and technologies in piecework alignment in turning can be sometimes be used to structure the milling knowledge and support milling decision.

An additional example of implicit knowledge is the know-how that can be structured about the ultrasonically assisted drilling in aluminium alloys that can help to reduce, and under some conditions completely eliminate the burring problem (Babitsky et al. 2003). This new technology concept has useful knowledge that can be implicitly used in milling and turning knowledge. It can be useful a concise explanation related to this new technology to support milling and turning decisions.

In this section process knowledge has been presented using explicit, tacit and implicit knowledge types. Technicians use different sources of process knowledge in hole manufacture according to the required hole accuracy and their expertise. Sometimes they apply only experience, personal notes or handbooks to get an answer. There is nothing wrong working individually in this manner, but it is important to obtain a method structuring the process knowledge contained in technicians' experiences, personals notes and handbooks to support future decisions. Three advantages can be obtained by structuring process knowledge a) the experienced technician can increase the value added in solving problems combining different experiences, b) Novice operators can learn following the knowledge structured, and c) wide range of new knowledge can be accessed using the different representations. In the next section, different resource knowledge examples are presented.

4.2.3.2 *Explicit and tacit resource knowledge*

Knowledge related to manufacturing resources have been structured using the different types of knowledge representations. The resource knowledge presented was structured to support process planning decisions for the samples I and II depicted respectively in Figure 4-3 and Figure 4-4. The knowledge represented in this section is mainly to support the hole making process. Through these representations, it was shown the wide range of resource knowledge that technicians use in a variety of manners to produce a hole. In the next sections tacit and explicit resource knowledge are explained.

Resource knowledge is structured information with added detail relating to how is used to support decisions in the production of a round hole. Resource knowledge describes how the resource can be used according to particular circumstances based on previous experiences. The resource knowledge presented in this section is to support decisions related to a twist drill before and after the drilling process is performed.

Standard Point
For general purpose drilling of steel, non-ferrous metals and plastics. The point angle varies with the application.

Form A
This form of Web Thinning is recommended in order to reduce the cutting pressure required to penetrate the work. The Web Thickness should be checked each time the drill is reground. Generally if the Web Thickness is over 10% of the diameter of the drill it is recommended to thin the point.

Form B
This form is recommended in order to provide better heat dissipation from the point. Also reduces the risk of point chipping on breakthrough when drilling high tensile materials.

Form C
This form is recommended in order to reduce the cutting pressure and provide more efficient chip removal. Specially suitable for deep hole drilling.

Form D
Double angle point recommended for cast iron and abrasive materials.

Form E
Centre Point. This point positions the drill easily and avoids burrs, producing exact and round holes in the thin sheet metal and pipes.

Form V
Four Facet Point. Designed for drilling small sized holes within narrow tolerances.

Form U
This new point form is a further development on all UFL drills as standard. The advantages are considerable and a further step towards the ultimate in performance for drilling truly deep holes. A combination of helix angle and cutting edge together with the special form of the point thinning improve chip formation and transportation.
The self centering point geometry produces a truly round hole in all soft materials and also enables very deep holes to be produced without the need for woodpecking.

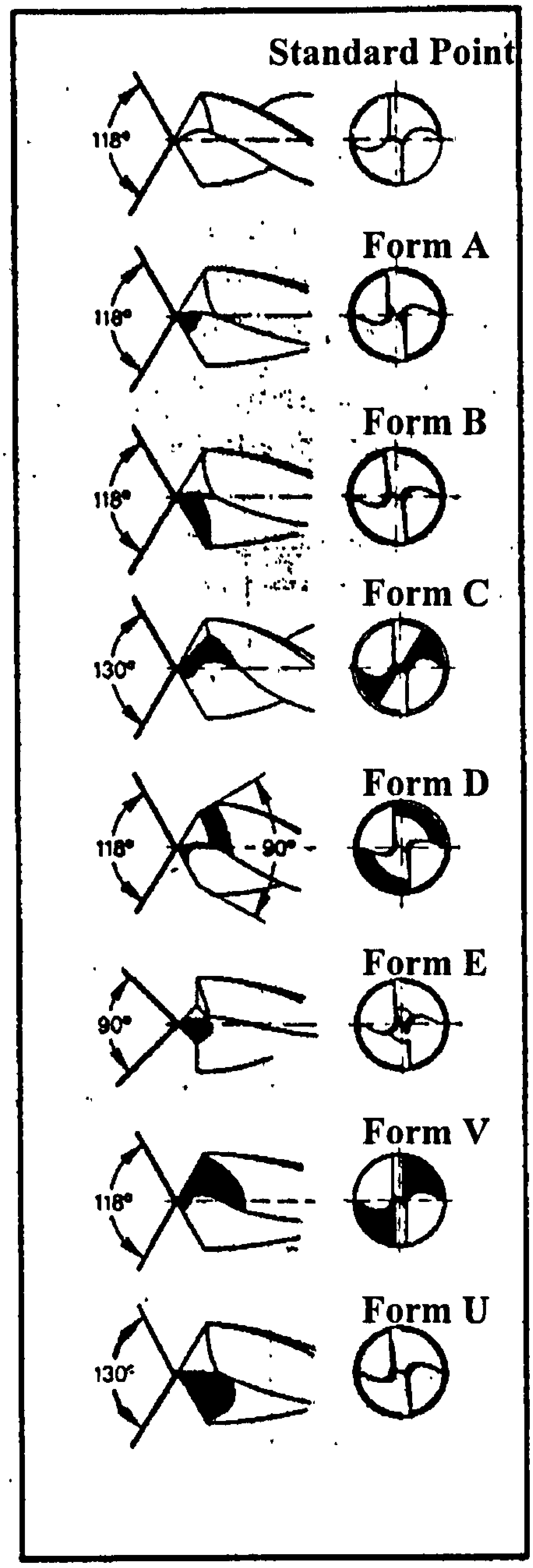


Figure 4-15 Tacit knowledge for recommended point angles and grinding forms (Titext 2003)

Before producing the work piece illustrated in Figure 4-3, sample I, the knowledge to select the twist drill to produce the 2 round holes it is not overly complex. The hole diameter and its length could be enough to select a suitable twist drill to manufacture these holes. Conventional KBS name this kind of knowledge as production rules which are knowledge and facts about a problem domain that can be represented as a rule in the form IF premises Then conclusions (Shehab and Abdalla 2002).

In the production of the work piece, there are kinds of knowledge related to the twist drill that are more difficult to represent in the form of production rules. To describe the knowledge to the resharpening of twist drills, different types of knowledge were required. For example, tacit knowledge using a sketch, and explicit knowledge using a procedure, and a graph were used. In the next paragraph a procedure is defined in combination with a sketch depicted in Figure 4-15 and a graph depicted in Figure 4-16.

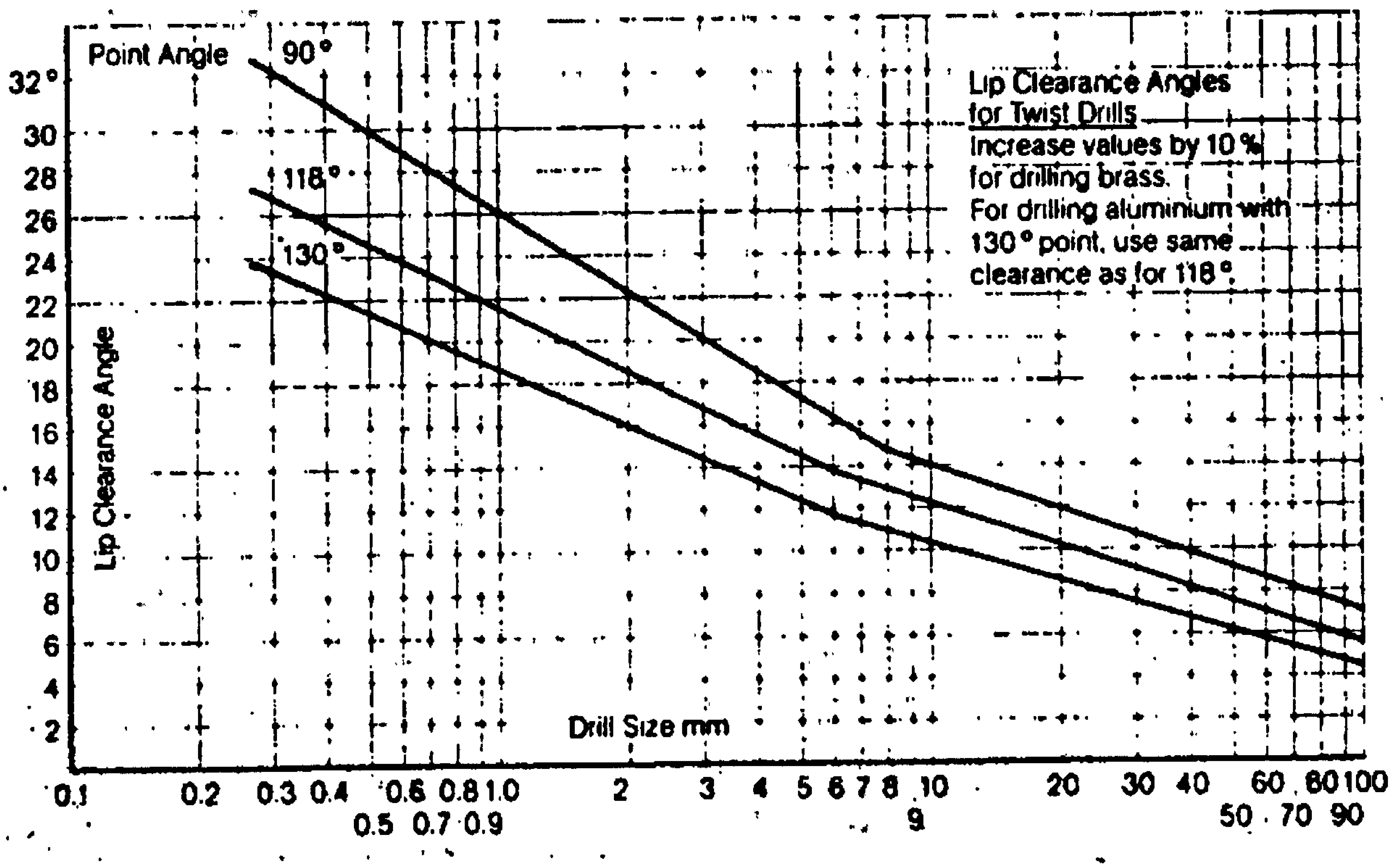


Figure 4-16 Explicit knowledge for resharpening of twist drill (Titext 2003)

The performance and life of the twist drill is dependent upon correct regrinding. The following procedure is recommended when regrinding is required (Titext 2003).

1. It is always advisable to review and regrind the drill before it becomes too dull. See sketch depicted in Figure 4-15 to select a proper drill point.
2. The cutting lips of the drill should be accurately ground and be equal in length.
3. Correct point angle should be maintained.
4. Regardless of point angle, the angles of the cutting lip should be equal.
5. Correct lip clearance angle should be maintained. After regrinding, graph depicted in Figure 4-16 illustrates the correct angles and vales for a standard drill.
6. Maintain relative lip height.
7. Check and correct web thickness. It is important that web thinning be done evenly with equal stock removal from each cutting edge.

An additional example where tacit knowledge representations are useful is to explain the types of coolant-fed drills and the coolant supply. Coolant-fed twist drills having means for directing coolant to the cutting edges offer many advantages for certain drilling applications (Oberg 1975). Figure 4-17 depicts a tacit knowledge representation for coolant-fed twist drill using a sketch.

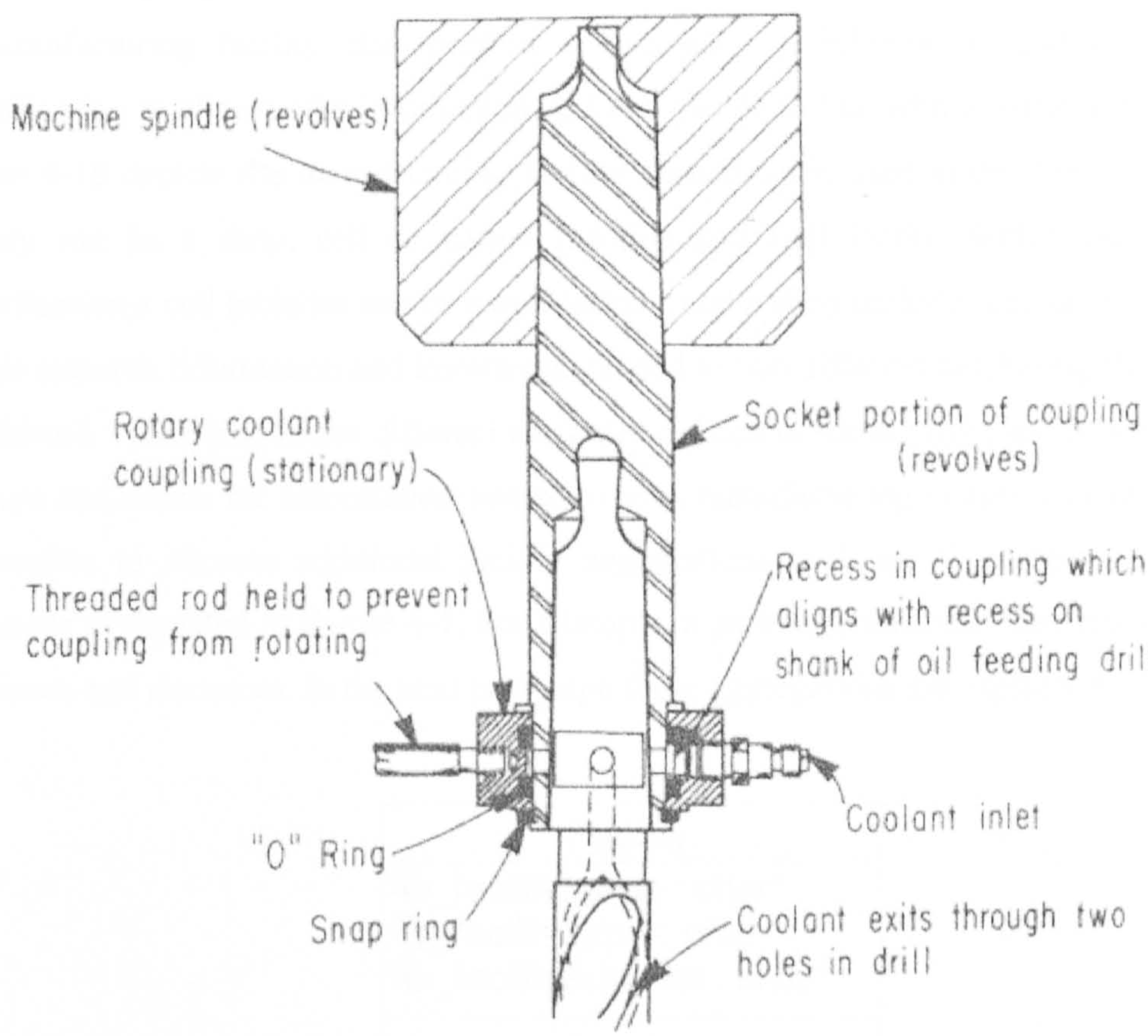


Figure 4-17 Tacit knowledge for coolant-fed twist drill (Oberg 1975)

Explicit, tacit and implicit types of knowledge can be used to represent process and resources knowledge and used to support process planning decisions in a manufacturing facility. The next issue is the definition of the information and knowledge structures to access and store the information and knowledge related to processes and resources allowing the knowledge maintenance in the manufacturing facility. The next section of this chapter explains the manufacturing information structures obtained for the MFIKM.

4.3. Manufacturing Information Structures

Following the discussion in section 4.2.2 this section discusses the organisation of manufacturing information into three main structures: a) facility information structure, b) process information structure, and c) resource information structure. The information to support process planning decisions for the samples I and II depicted respectively in Figure 4-3 and Figure 4-4 was structured to analyse how the structures works. ISO standards were as well consulted in the structures created. These three structures are explained in the next sections.

4.3.1. Facility Information Structure

A manufacturing facility classification is necessary in information and knowledge identification to allocate the information and knowledge in line with a particular facility. Figure 4-18 depicts the manufacturing facility classification used in this thesis where a facility can be a shop, cell or station (Molina and Bell 1999). Within the facility classification a cell includes one or more stations, and a shop includes one or more cells. In this research information and knowledge related to two different machining shops was considered. According to the different attributes defined to the facility class it is possible to store and access the information related to each manufacturing facility considered. It is possible to allocate additional facility aggregations such as: a) processes, and b) resources as depicted in Figure 4-1. For example, a particular machine shop has specific processes and resources. In the next paragraph these aggregations are explained.

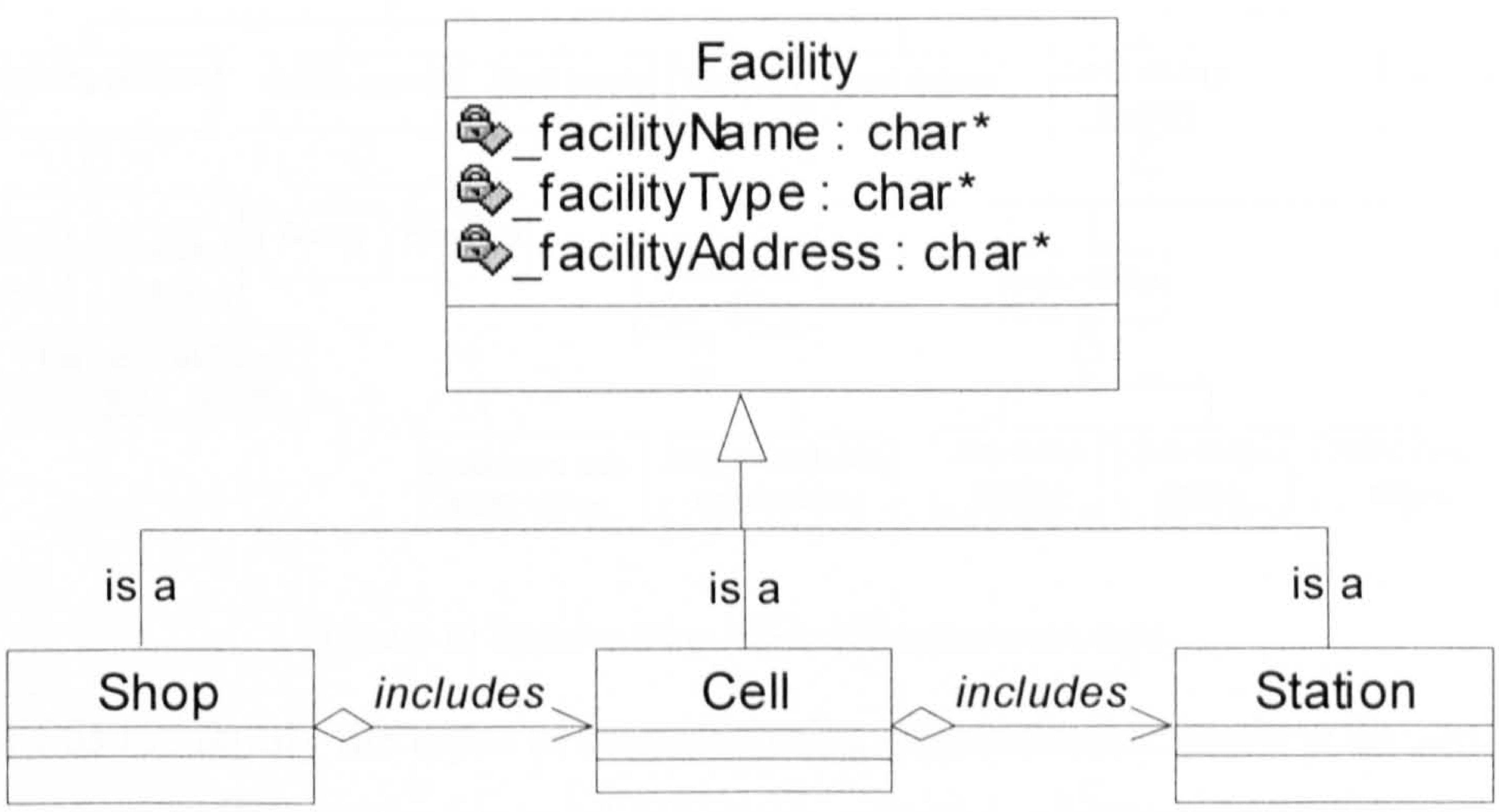


Figure 4-18 Manufacturing facility classification. Adapted from (Molina and Bell 1999)

4.3.2. Processes Information Structure

Creation of a process information structure allows the information classification related to manufacturing facility processes. Different process categorisations can be considered depending on a particular manufacturing facility. For example the process structure required can be different if the facility considered is to produce an electronic device instead of a machined part. There is a need to create a process information structure in a manufacturing facility because a manufacturing processes definition is required and align this definition with the current manufacturing facility processes.

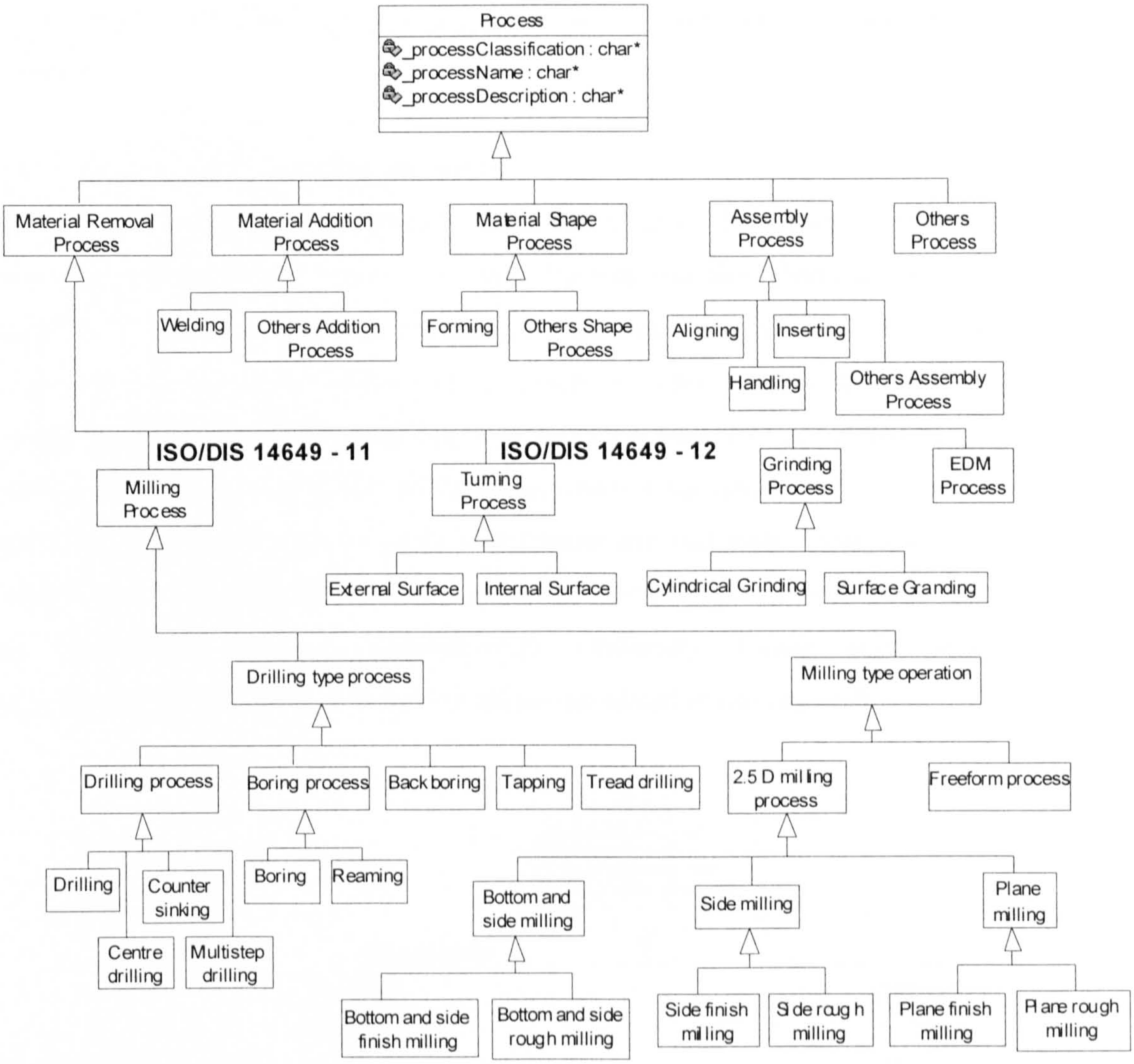


Figure 4-19 Manufacturing information process structure

An issue was to identify the types of manufacturing processes that needs to be considered in a manufacturing facility. Material removal, material addition, material shape and assembly were considered conventional manufacturing processes to produce a machined part (Chang et al. 1998). Molina and Bell (Molina and Bell 1999) explored a processes classification using a general process definition and presenting some machining processes. However, in order to provide sufficient information for hole making processes, additional process classification in milling and turning processes at shop facility level was required. For this reason ISO/DIS 14649 -11 standard was used as a reference to categorise the milling process within material removal processes. In addition, ISO/DIS

14649 – 12 standard was used as reference document for turning. The material removal process categorisation considered the ISO standards mentioned to clarify the manufacturing processes definition. The manufacturing processes definition was populated with information from two machining shops at Loughborough University. Figure 4-19 depicts the manufacturing information process structure considered in this research.

4.3.3. *Resources Information Structure*

The creation of a resource information structure requires the information classification related to manufacturing facility resources. Molina and Bell (Molina and Bell 1999) explored a resource classification using a general resource definition. However, additional resource classification was required in order to align the wide range of resources that a manufacturing facility has. For this reason IEC/DIS 62264 standard was used as a reference to categorise the resources within a manufacturing facility. This thesis only covers physical resources such as equipment and materials within a manufacturing facility. The manufacturing resource definitions were populated with information from two machining shops at Loughborough University. Figure 4-20 depicts the manufacturing information resource structure considered in this research.

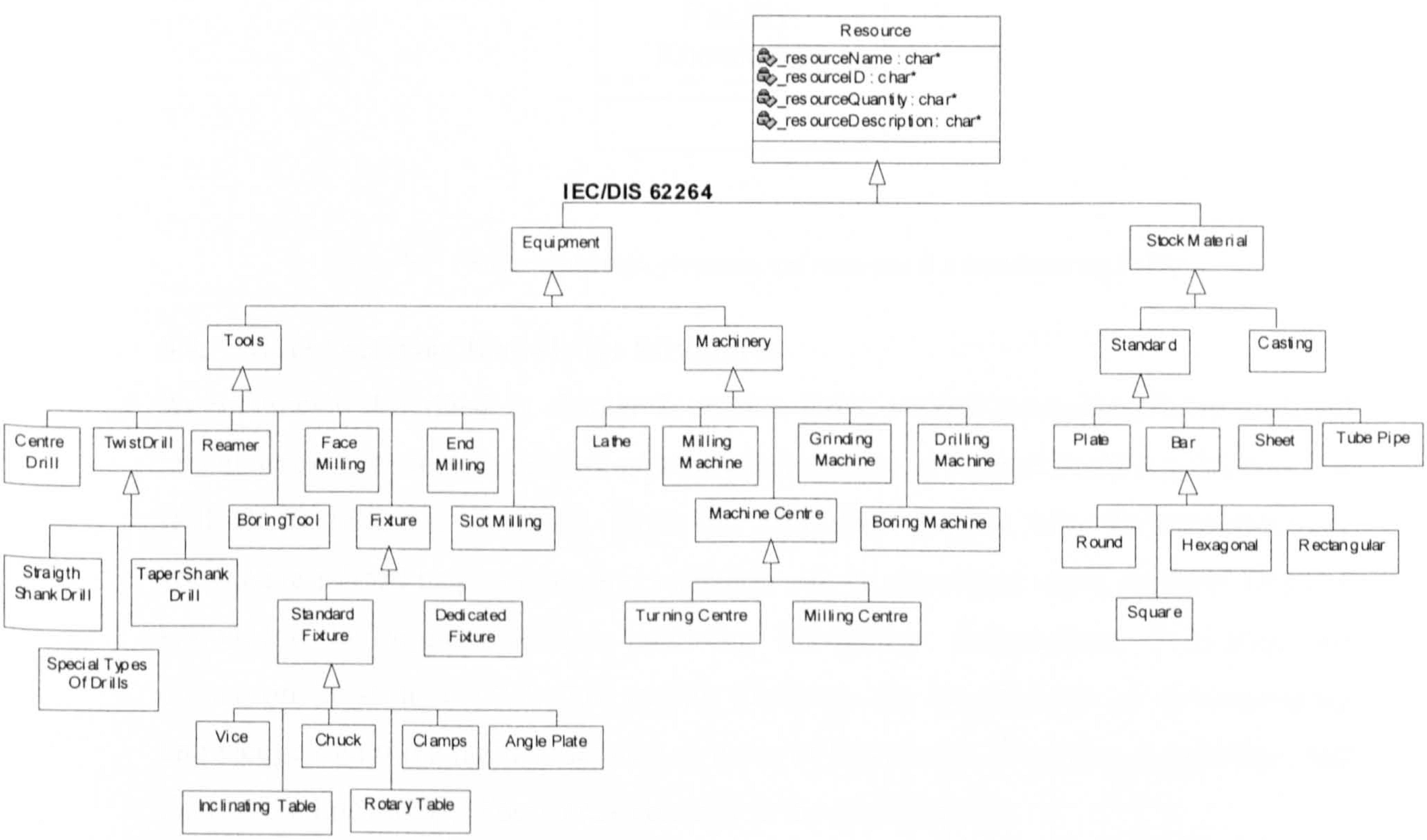


Figure 4-20 Manufacturing information resource structure

Figure 4-20 provides the basis for the representation of the resource information used in this research. Tools, machinery and stock material can be considered as main manufacturing resources to produce a machined part using material removal processes. Figure 4-20 shows the extended general resource information structure for the MFIKM used in this research.

According to Figure 4-19 and Figure 4-20, it can be observed that the information structures are largely based on existing ISO standards combined with Molina and Bell's (Molina and Bell 1999) general structures. The novelty presented here is how to link this with knowledge representations. Figure 4-21 shows the new facility knowledge class for storing facility knowledge related to process and resources to support process planning decisions. The manufacturing knowledge structures to capture the facility knowledge are discussed in the next section.

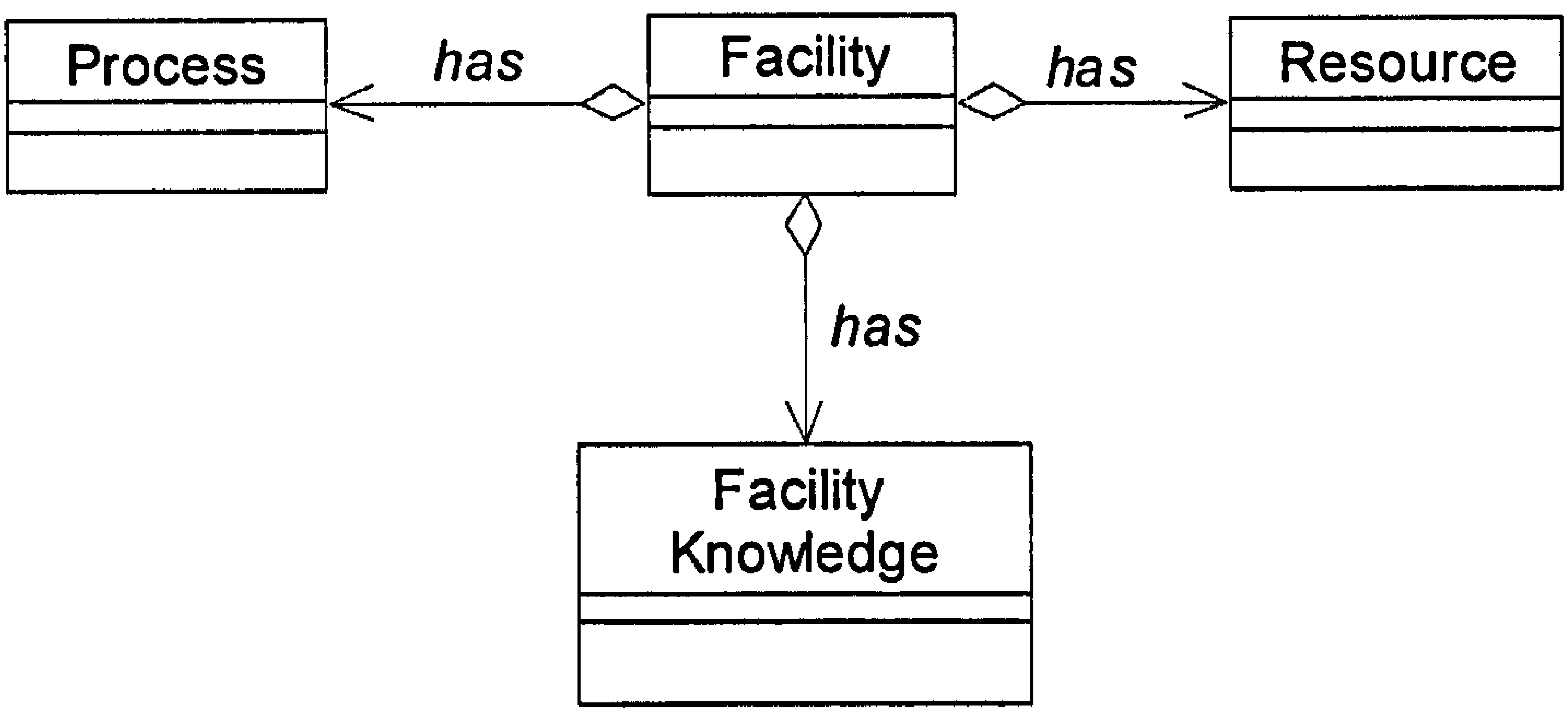


Figure 4-21 Facility knowledge, processes, and resources in a manufacturing facility

4.4. Manufacturing Knowledge Structures

As previously described in chapter 2, section 2.4.4, several researchers have explored manufacturing strategies organising facility information to support decisions (Molina and Bell 1999), (Zhao et al. 1999). However, they don't explore how the manufacturing knowledge related to processes and resources can be structured using different types of knowledge to support decision allowing knowledge maintenance. Following the discussion in section 4.2.3, this section discusses the organisation of manufacturing knowledge into three main structures: a) types of knowledge, b) process knowledge, and c) resource knowledge. These are explained in the next sections.

A main issue was how to determine and categorise the knowledge in a manufacturing facility. Different knowledge structures were explored, for example the knowledge as a resource and process attribute was considered. However, because of the large and different types of knowledge this option is very difficult to implement. After several tests it was found that two super classes provide wide range of the facility knowledge categorisation. This first super class was named facility knowledge where the knowledge related to processes and resources is categorised. An additional class was titled types of knowledge and is used to categorise the current knowledge types. The combinations of these super classes make possible the manufacturing facility categorisation. In the next paragraphs this idea is discussed.

The whole manufacturing knowledge is organised in a facility knowledge super class that is divided into process knowledge and resource knowledge respectively. The facility knowledge super class can include different manufacturing knowledge such as: grinding, EDM, lapping, casting, etc. However, two main classes are considered in process knowledge that are milling knowledge and turning knowledge according to the research scope. Figure 4-22 shows a facility knowledge classification defined to the MFIKM. The whole process knowledge explained in section 4.2.3.1 is organised in the milling and turning subclasses defined in Figure 4-22. In a similar manner three main classes are considered to the resource knowledge: machinery, tool and material.

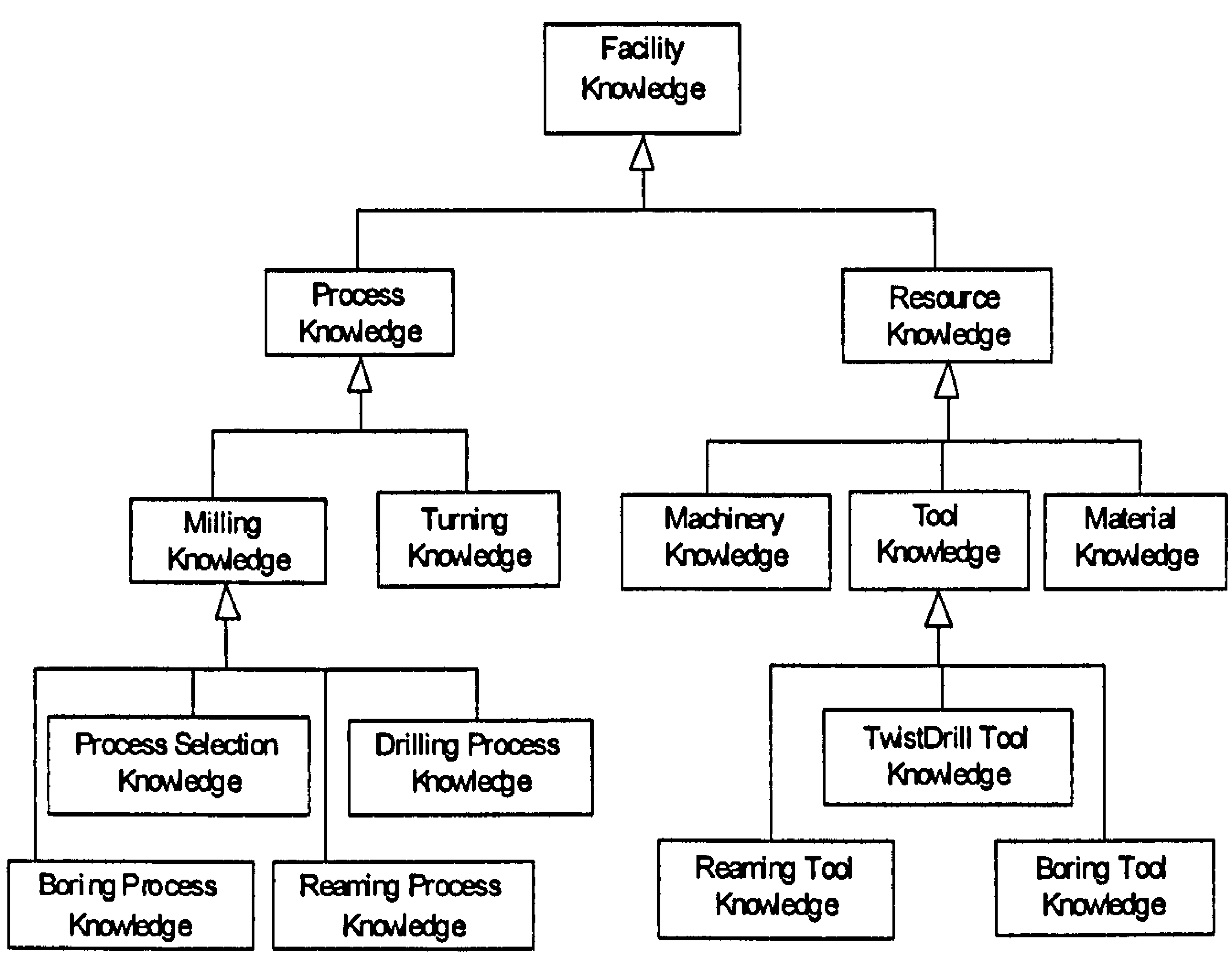


Figure 4-22 Facility knowledge classification

Creation of knowledge structures requires understanding of the knowledge subject and object oriented concepts. The knowledge subject is performed by the know-how required to support particular decisions. See section 4.2.3 for particular process and resource knowledge. The knowledge categorisation needs to be according to the object-oriented concepts. See appendix A for the object-oriented concepts. For example, drilling, reaming and boring have been defined as knowledge subject but can also be considered as milling sub processes and as a consequence can inherent all the process knowledge super class attributes. Drilling, reaming and boring processes have been considered as milling processes according to the ISO/DIS 14649 -11 standard. However, these milling processes can be performed in a lathe. The whole knowledge related with drilling, reaming and boring processes performed in a lathe is considered in the turning knowledge super class.

4.4.1. Types of Knowledge Structure

According to the different types of knowledge defined previously in chapter 2, section 2.2.3, this section discusses the organisation of these knowledge types according to object-oriented concepts.

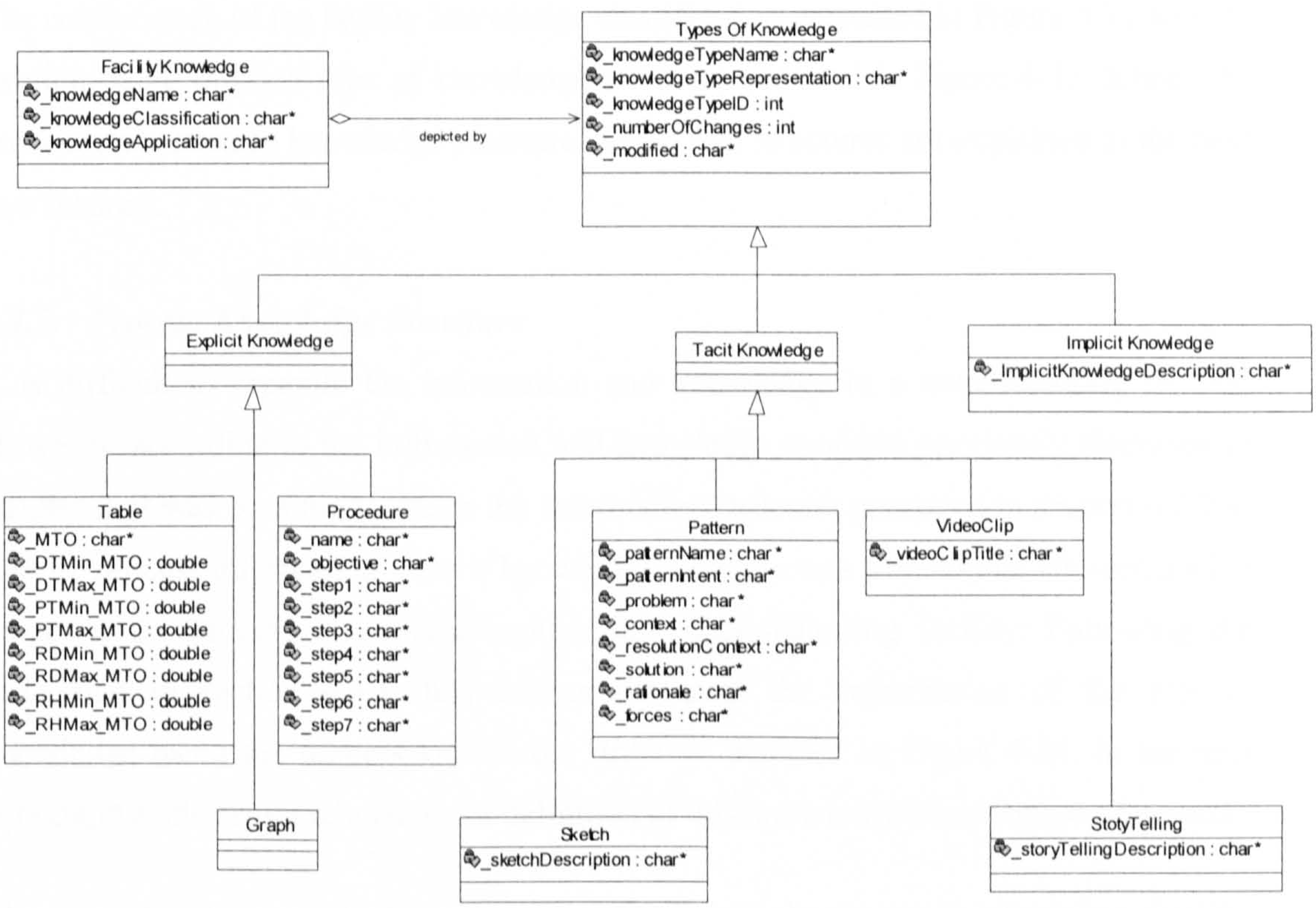


Figure 4-23 Explicit, tacit implicit type of knowledge structure.

It is required to define a super class to organise different types of knowledge and use them to access the facility knowledge. A super class named types of knowledge is defined to organise the current knowledge types in a manufacturing facility. Explicit, tacit, and implicit knowledge are considered as subclasses of the types of knowledge super class. The explicit knowledge described is divided in table, graph and procedure subclasses. In similar manner, the tacit knowledge can be divided in sketch, pattern, video clip and storytelling. The implicit knowledge is considered in the implicit knowledge class. Figure 4-23 shows the explicit, tacit implicit type of knowledge structure to represent facility knowledge.

It is important to define suitable attributes according to the type of knowledge definition and the particular knowledge representation in order to capture the right knowledge in the right format. For example, the type of knowledge super class has the attributes such as: name, type of representation, identification (ID), number of changes, and modified date in order to manage each facility knowledge instance created. In addition, each type of knowledge representation subclass has particular attributes as can be observed in Figure 4-23.

The combination of the facility knowledge classification presented in Figure 4-22 and the explicit, tacit, implicit type of knowledge structure depicted in Figure 4-23 defines the process and resource knowledge structure. These two structures are explained in the next two sections.

4.4.2. Process Knowledge Structure

It is difficult to separate the information and knowledge in a manufacturing facility. However, according to the information and knowledge concepts previously discussed in chapter 2, it was possible to create the information structure presented in section 4.3.2 to capture process information. A new knowledge structure was created that allowed a wide range of the process knowledge capture in a manufacturing facility. Following the discussion in section 4.4.1, this section discusses the organisation of the process knowledge using the process knowledge structure depicted in Figure 4-24. In the next paragraph some issues related to the definition of this knowledge structure are presented.

There are large amounts of complex process knowledge in a manufacturing facility. However, the process knowledge to support process planning decisions for the samples I and II depicted respectively in Figure 4-3 and Figure 4-4 was used as scope to analyse how the knowledge structure works. Thinking in the hole making process it was identified the main milling and turning piece of process knowledge to support the manufacture of samples I and II. The knowledge structure obtained allows the capture of the processes knowledge presented in section 4.2.3.1.

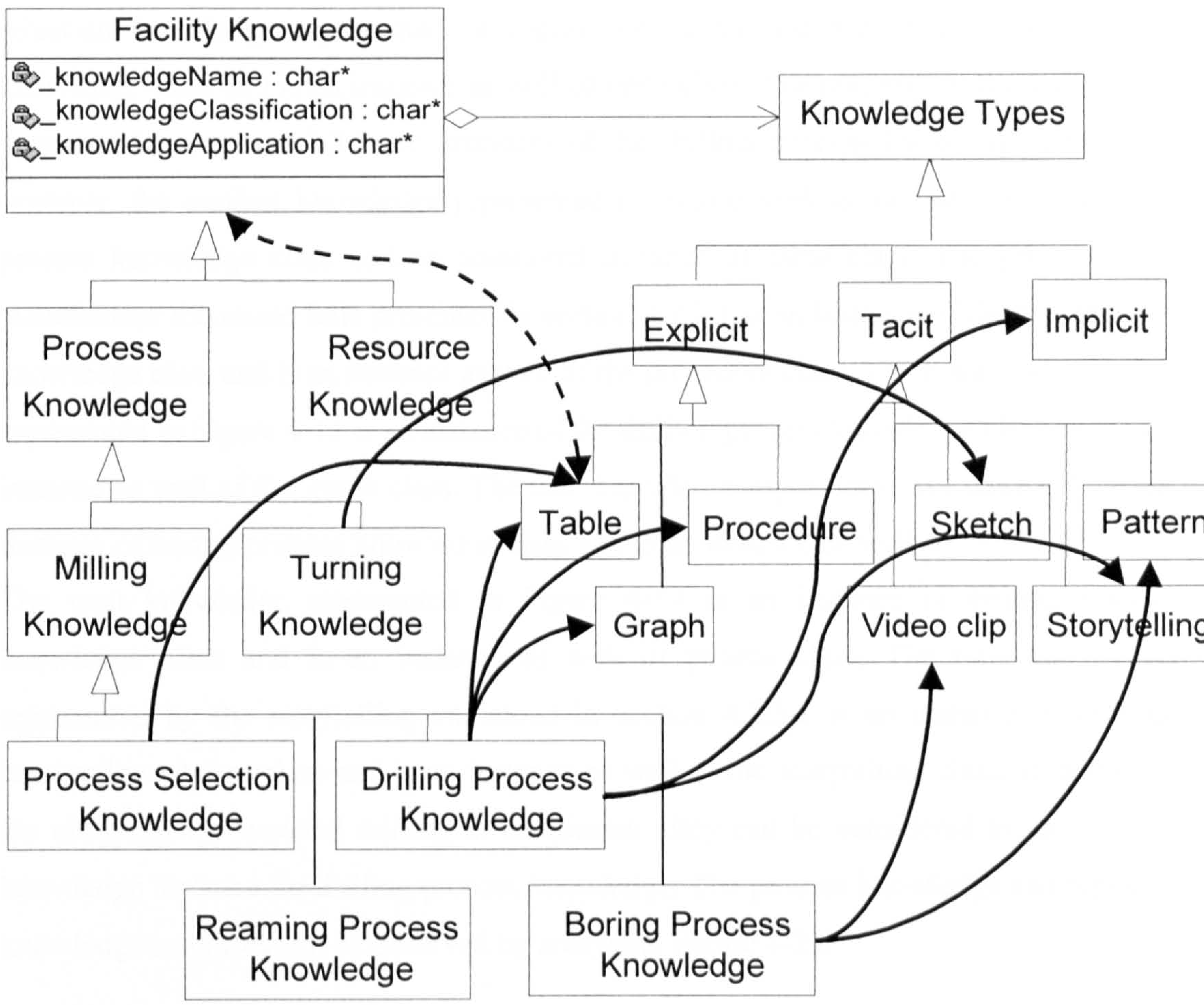


Figure 4-24 Process knowledge structure.

An additional issue is to define the right process knowledge attributes to enable suitable process knowledge identification and classification. The attributes such as name, classification, and application have been defined to identify the facility knowledge instances. In this case, according to Figure 4-24, the knowledge name is process knowledge and the classification could be milling or turning knowledge. In addition, the definition of knowledge application depends on the drilling, reaming or boring knowledge subject. As a consequence, each instance of the classes: process selection, drilling process, reaming process, and boring process can be represented by explicit, tacit or implicit knowledge. According to the arrows depicted in Figure 4-24 it is possible to identify the connection of the different process knowledge instances considered. The next paragraph discusses how the structure works accessing the process knowledge instances mentioned in section 4.2.3.1.

The turning knowledge represented in Figure 4-13 is an instance of turning knowledge class and is an instance as well of the sketch class. In a similar manner the process selection knowledge represented in Figure 4-9 is an instance of process selection knowledge class and is an instance as well of table class. The majority of the knowledge discussed in section 4.2.3.1 are instances of the drilling process knowledge class. For example, the explicit knowledge represented in Figure 4-10 is an instance of drilling process knowledge class and an additional instance of table class. The procedure to manufacture the round hole presented in section 4.2.3.1 is an instance of drilling process knowledge class and is an instance as well of the procedure class. The explicit knowledge represented in Figure 4-11 is an instance of the drilling process knowledge class and is an instance as well of the graph class. The tacit knowledge represented in Figure 4-12 is an instance of boring process knowledge class and is an instance as well of video clip class. The tacit knowledge represented in Figure 4-14 is an instance of boring process knowledge class and is an instance as well of pattern class. The tacit knowledge represented by the storytelling explained in section 4.2.3.1 is an instance of drilling process knowledge class and is an instance as well of the storytelling class. In addition, the ultrasonically assisted drilling in aluminium alloy can be considered as an implicit knowledge instance for drilling process knowledge. The process knowledge and types of knowledge instances can be observed by analysing Figure 4-24.

4.4.3. Resource Knowledge Structure

This section discusses the organisation of the resource knowledge using a new resource knowledge structure depicted in Figure 4-25 to capture the resource knowledge in a manufacturing facility. In the next paragraphs some issues related to the definition of this knowledge structure are presented.

It is not easy to identify differences between information and knowledge related to manufacturing resources. However, according to the information and knowledge concepts previously discussed in chapter 2, it was possible to organise the resource information in the structure explored in section 4.3.3 and the resource knowledge in the new resource knowledge structure created and depicted in Figure 4-25.

There is massive, complicated and valuable resource knowledge in a manufacturing facility that can be captured to support decisions. However, the resource knowledge to support process planning decisions for the samples I and II depicted respectively in Figure 4-3 and Figure 4-4 was used as scope to analyse how the knowledge structure works. Thinking in the hole making process, the main milling and turning piece of process knowledge was identified to support the manufacture of samples I and II. The knowledge structure obtained allows the capture of the resource knowledge presented in section 4.2.3.2.

An additional issue is to define the resource knowledge attributes to enable resource knowledge capture. Similar to process knowledge, resource knowledge is a subclass of the facility knowledge super class. Figure 4-25 depicts the facility knowledge super class attributes, the knowledge name is resource knowledge and the classification and application depends on the machinery, tool or material knowledge. Subsequently, the instances of the knowledge classes of reaming tool, boring tool or twist drill tool can be represented by explicit, tacit or implicit knowledge. According to the arrows depicted in Figure 4-25 it is possible to identify the connection of the different resource knowledge instances considered. The next paragraph discusses how the structure works accessing the resource knowledge instances mentioned in section 4.2.3.1.

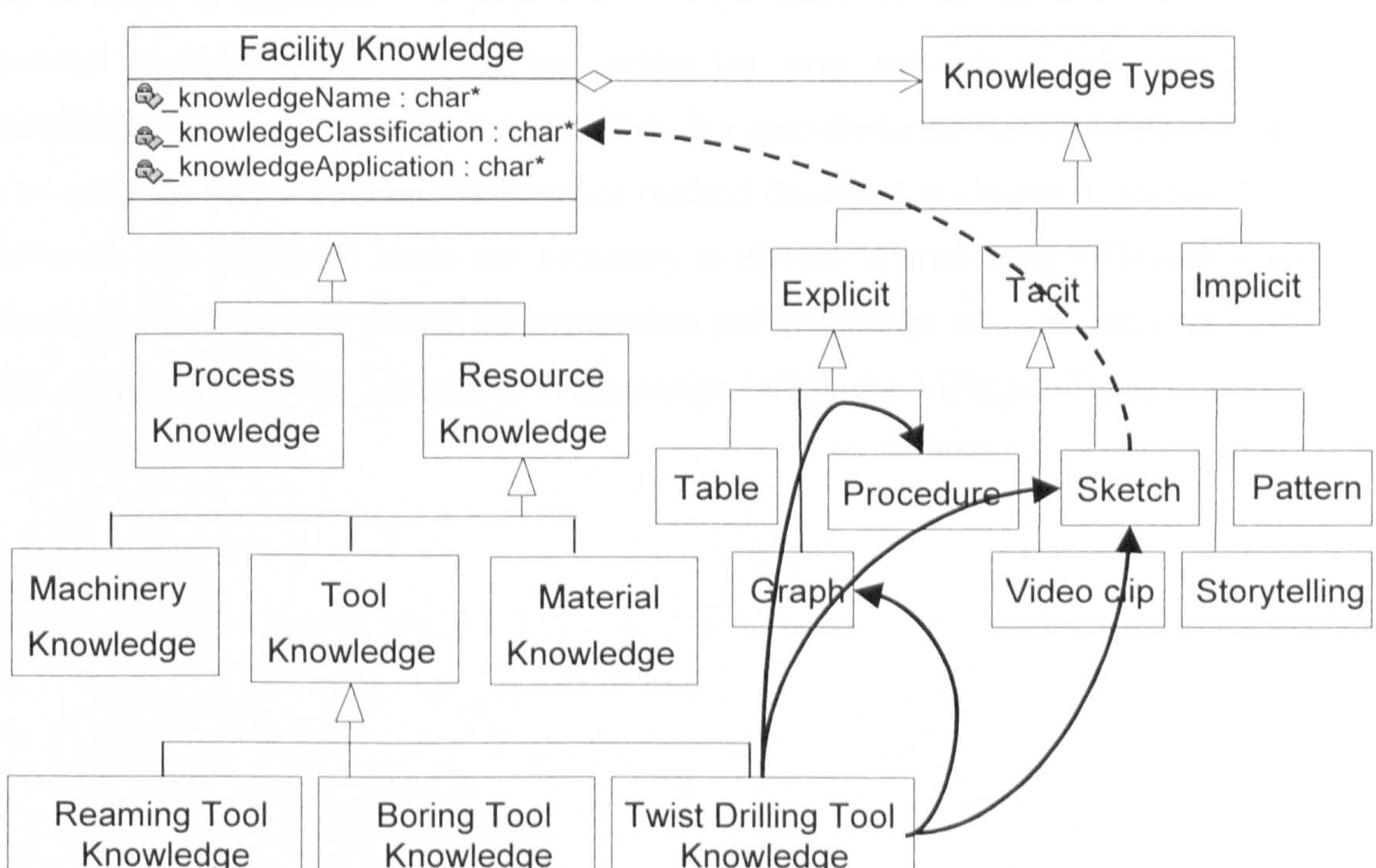


Figure 4-25 Resource knowledge structure.

The resource knowledge explained in section 4.2.3.2 are instances of the twist drill tool knowledge class using the different knowledge types. The tacit knowledge represented in figures Figure 4-15 and Figure 4-17 are instances of twist drill tool knowledge class and are also two additional instances of the sketch class. The procedure to regrind a twist drill as presented in section 4.2.3.2 is an instance of twist drill tool knowledge class and is an instance as well of the procedure class. In addition, the explicit knowledge represented in Figure 4-16 is an instance of twist drill tool knowledge class and is as well an instance of the graph class. The resource knowledge and types of knowledge instances can be observed according to the arrows depicted in Figure 4-25. The facility knowledge and the types of knowledge instances related to processes and resources will be clarified in chapter 6 using the experimental software application developed.

4.5. Information and Knowledge Structures for the MFIKM

In this section the final MFIKM structure is presented and the need of facility information and facility knowledge location and relationships within the Model in order to support knowledge maintenance is emphasised.

Figure 4-26 depicts the final MFIKM structure after several versions organising the information and knowledge in a manufacturing facility. An extended UML version of this structure in appendix C is presented. A major issue was solved with the MFIKM structure provided because it can be capture the large amounts of information and knowledge related to processes and resources in a manufacturing facility. The next step is to apply the manufacturing maintenance method discussed in chapter 3, section 3.3.2. However, two additional issues are necessary to discuss to enable the information and knowledge maintenance. Define the information and knowledge location, and explore the kind of information and knowledge relationships within the MFIKM. These issues are discussed in chapter 5.

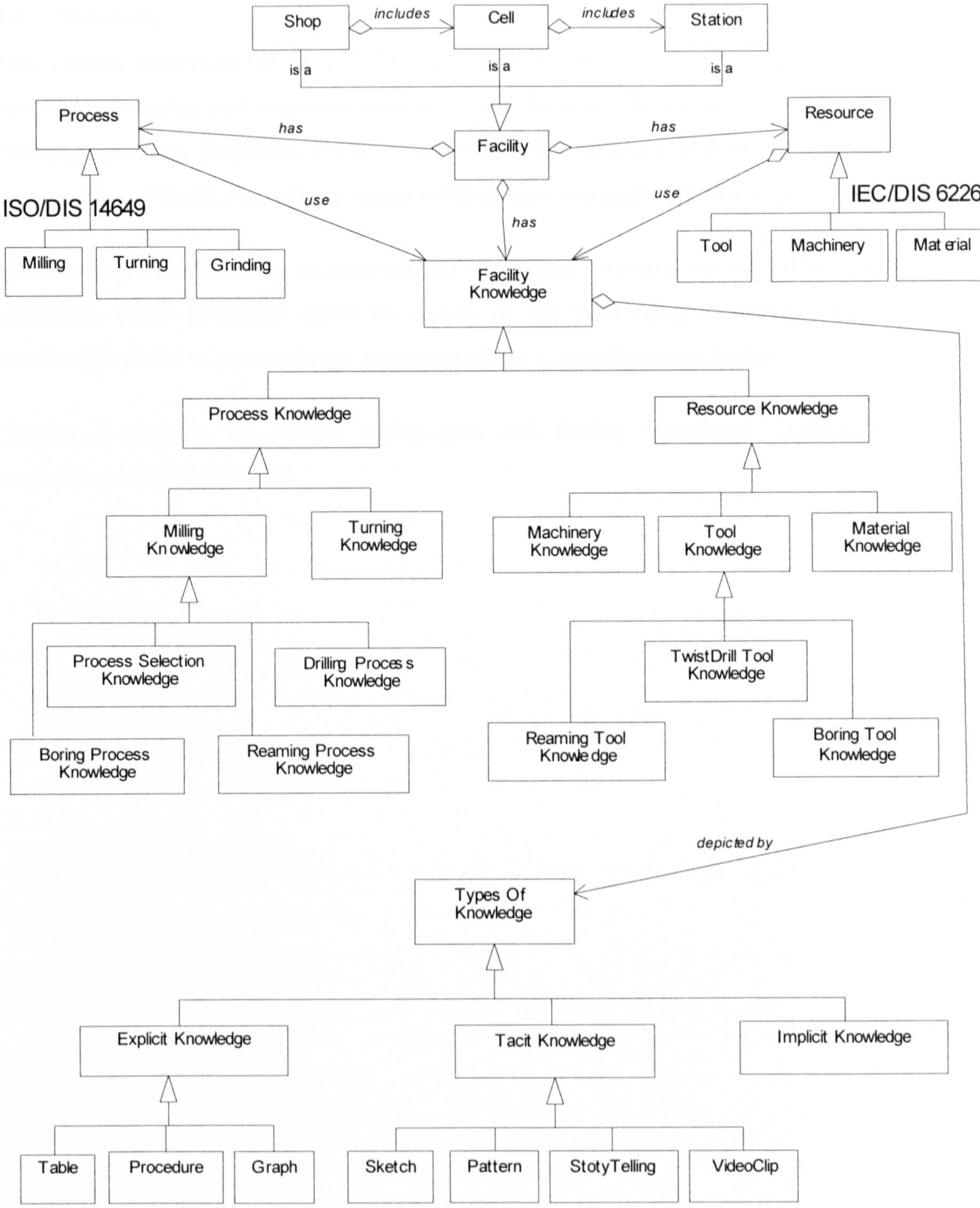


Figure 4-26 Information and knowledge structures in the MFIKM

4.6. Summary

This chapter presented the main differences between the information and knowledge related to processes and resources used in a manufacturing facility to support process-planning decisions. Emphasis was set in the knowledge structure to store and access the large amount of facility knowledge using explicit, tacit and implicit knowledge.

The resulting manufacturing information and knowledge structures for the MFIKM were presented. These structures allow the access of the wide range of information and knowledge related to processes and resources within a manufacturing facility.

Chapter 5 explains the facility information and facility knowledge location and relationships for the MFIKM.

CHAPTER 5

5. LOCATION AND RELATIONSHIPS OF THE INFORMATION AND KNOWLEDGE WITHIN THE MFIKM

5.1. Introduction

This chapter explores the location and relationships of the information and knowledge within the MFIKM to support knowledge maintenance.

Four main sections are reported in this chapter. The first section explains the facility information and facility knowledge location within the MFIKM. The second section discusses individually the facility information relationships and the facility knowledge relationships. The third part presents the information and knowledge relationships related to processes and resources explaining the combination of information and knowledge to support process-planning decisions. The fourth section explores the new information and knowledge maintenance and its relationships. In addition to presenting the location and relationships of the information and knowledge, this chapter establishes the interactions between information and knowledge structures that will be validated in chapter 6.

5.2. Facility information and facility knowledge location with in the MFIKM

Following the discussion in chapter 4, this section discusses the location of the facility information and facility knowledge in the MFIKM structures. The issue related to the use of the information and knowledge in this manner is discussed below.

As previously discussed in chapter 3, section 3.3.2 the information and knowledge location in the knowledge maintenance life cycle is a significant issue. For this reason it is necessary to determine the information and knowledge location within the MFIKM to enable the information and knowledge maintenance.

It is possible to capture facility information and facility knowledge separately within the MFIKM. Consistent with the information and knowledge definitions discussed in chapter 2, section 2.2.2 and the manufacturing facility structures explored in chapter 4, sections 4.3 and 4.4, the information and knowledge can be stored separately within the MFIKM. Therefore, the manufacturing information structures discussed in section 4.3 allow the facility information location. Similarly, the manufacturing knowledge structures discussed in section 4.4 allow the facility knowledge location.

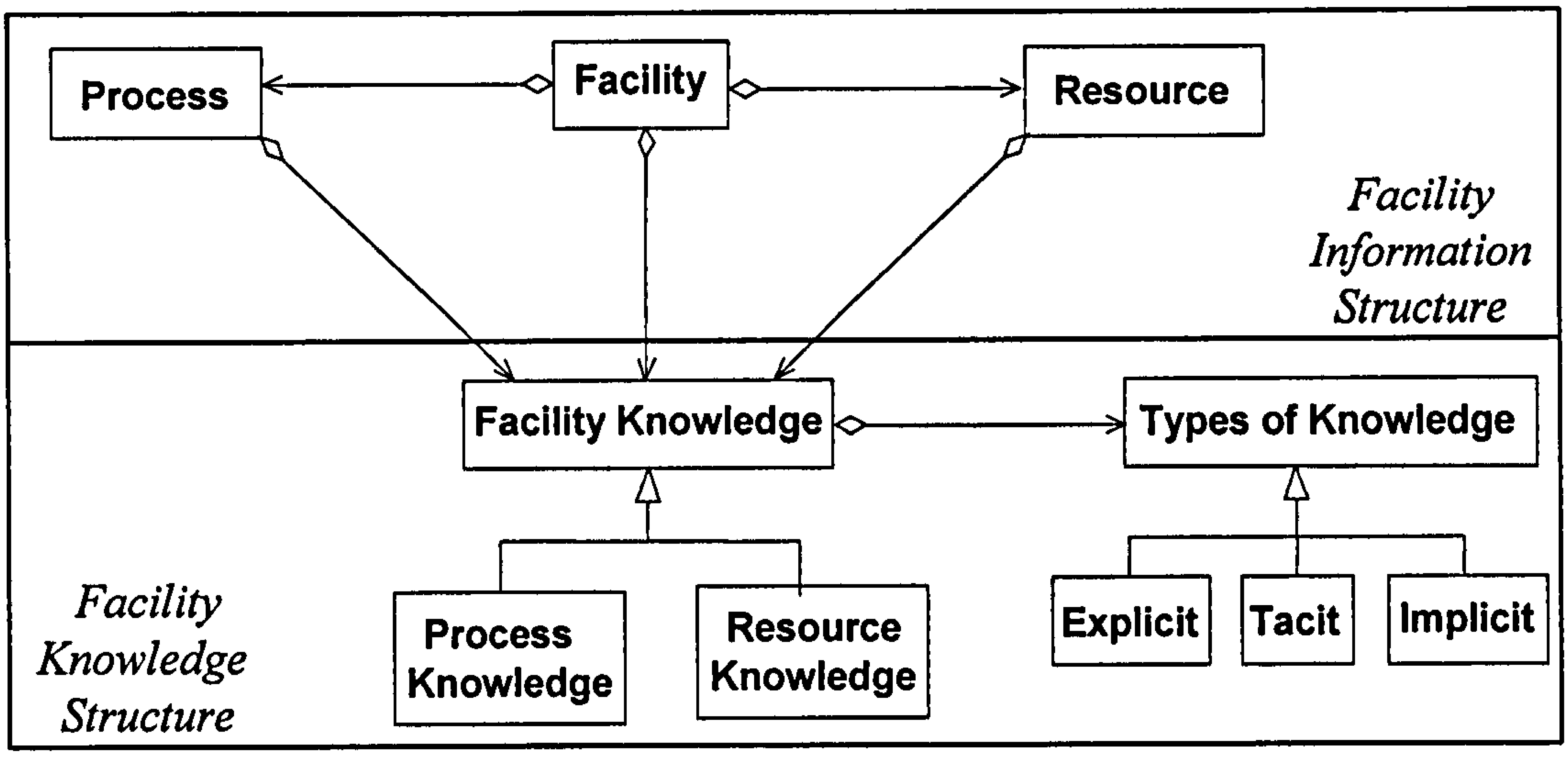


Figure 5-1 Information and knowledge location

Figure 5-1 illustrates the information and knowledge location in the MFIKM. The *process*, *facility* and *resource* super classes capture the information related to a manufacturing facility. In a similar manner the *facility knowledge* and *types of knowledge* super classes capture the knowledge related to a manufacturing facility. As a consequence, the *process*, *facility* and *resource* super classes determine the manufacturing facility information location and the *facility knowledge* and *types of knowledge* super classes determine the manufacturing facility knowledge location.

5.3. Facility information and facility knowledge relationships

The facility information relationships and the facility knowledge relationships are explored individually in this section. It is necessary to explain the association between information and knowledge related to processes and resources to understand the facility information and facility knowledge relationships. However, it is important to explain individually the facility information relationships and the facility knowledge relationships before showing the interactions between these two. The reason is because it is important to comprehend the kinds of information and knowledge captured in the MFIKM to enable the information and knowledge maintenance.

Figure 5-2 illustrates the issue of relationships between information and knowledge structures. The MFIKM discussed in chapter 4, organises the facility information and facility knowledge required to produce two machining examples at two Loughborough University machining shops. Figure 5-2 emphasise the relationships with question marked arrows that are discussed in the next sections. Section 5.3.1 discusses the facility information relationships and section 5.3.2 the facility knowledge relationships individually. The relationship between the facility information and the facility knowledge represented by the question marked arrow is discussed in section 5.4.

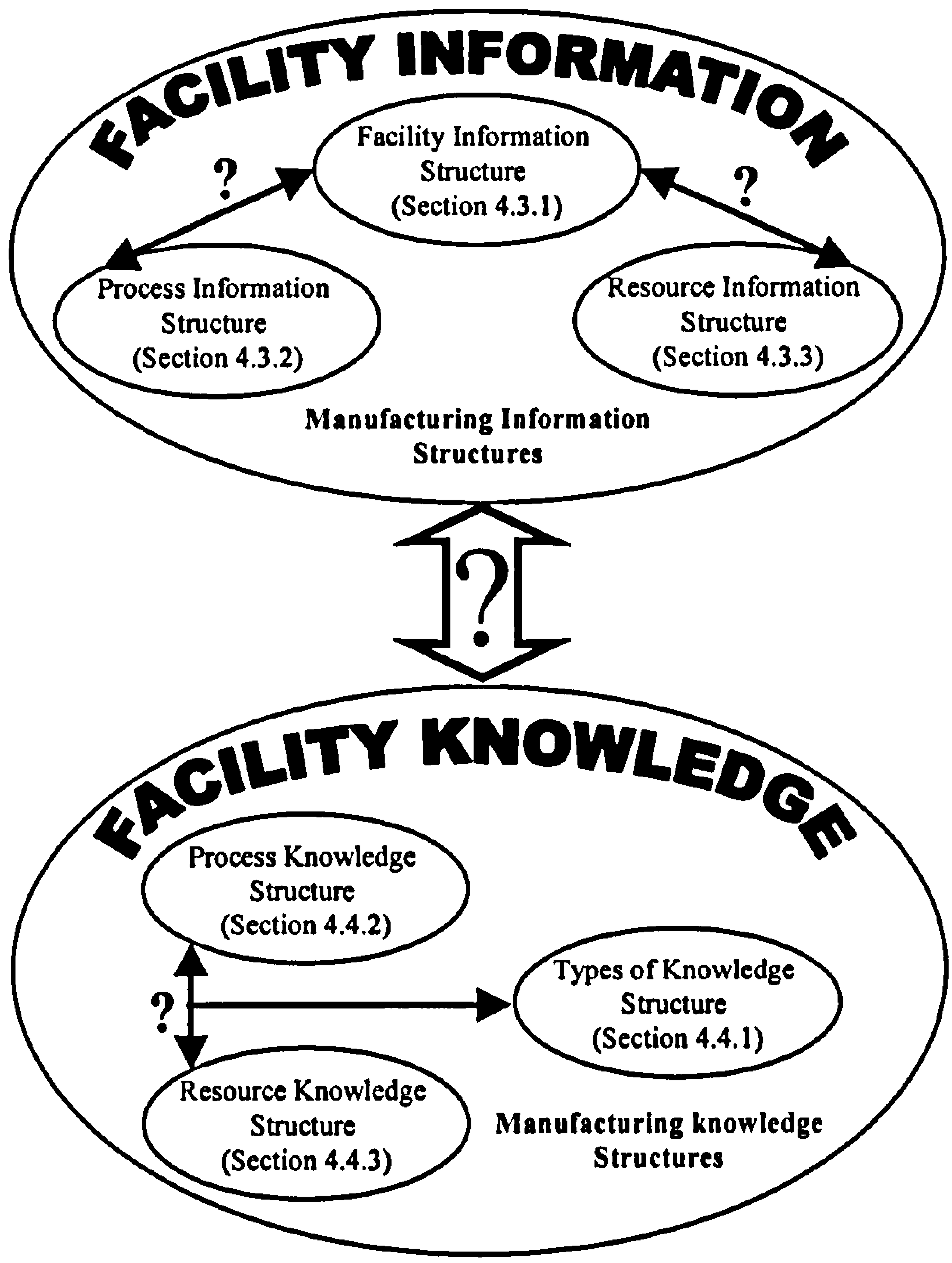


Figure 5-2 Facility information and facility knowledge relationship

5.3.1. Facility information relationships

Facility information is the data organised consistent with the manufacturing information structures illustrated in the upper part of Figure 5-2. The MFIKM captures the facility information according to three structures: a) facility information structure, b) process information structure, and c) resources information structure.

Three kinds of information can be obtained in a manufacturing facility. Information related to facilities. Information related to processes and information related to resources. Figure 5-3 shows the three information structures that have been used to organise facilities, processes and resources for two shops at Loughborough University. The facility information structure has been used to organise information related to stations, shops, and cells. The kind of facility information captured is the name, type, and address for each facility. The process information structure has been used to organise information related to milling and turning processes. The kind of process information captured is the classification, name, and description for each process. The resource information structure has been used to organise resource information related to tools, machineries, and materials. The kind of information captured is the name, identification (ID), quantity, and description for each resource. In addition, the resource information considers the tool, machinery, and material attributes depicted in Figure 5-3.

There are four kinds of information relationships in a manufacturing facility. Information relationships related to a) facilities, b) processes, c) resources, and d) combination of facilities, processes and resources. Figure 5-3 illustrates theses relationships. It can be observed that the first three relationships depend on facility, process and resource super classes. The combination of facilities, processes and resources information depend on facility, process and resource relationship. The fourth kind of information relationship is shown in bold lines in Figure 5-3 and by question marked arrows in the upper part of Figure 5-2. The four kinds of information relationships in a manufacturing facility are explained next.

The information relationships related to facilities are the connected information obtained from shops, cells and station information. For example, the particular stations and cells that belong to each shop can be identified. In a similar manner, process information relationships are the machining process information that belongs to milling and turning processes. The resources information relationships are the machining resource information that belongs to tool, machinery, and material. The combination of facilities, processes and resources information is, for example, when a particular shop is aligned with particular processes and resources in a manufacturing facility. The facility information relationships make available information contexts providing useful manufacturing meaning. The information contexts are obtained as a result of the information relationships.

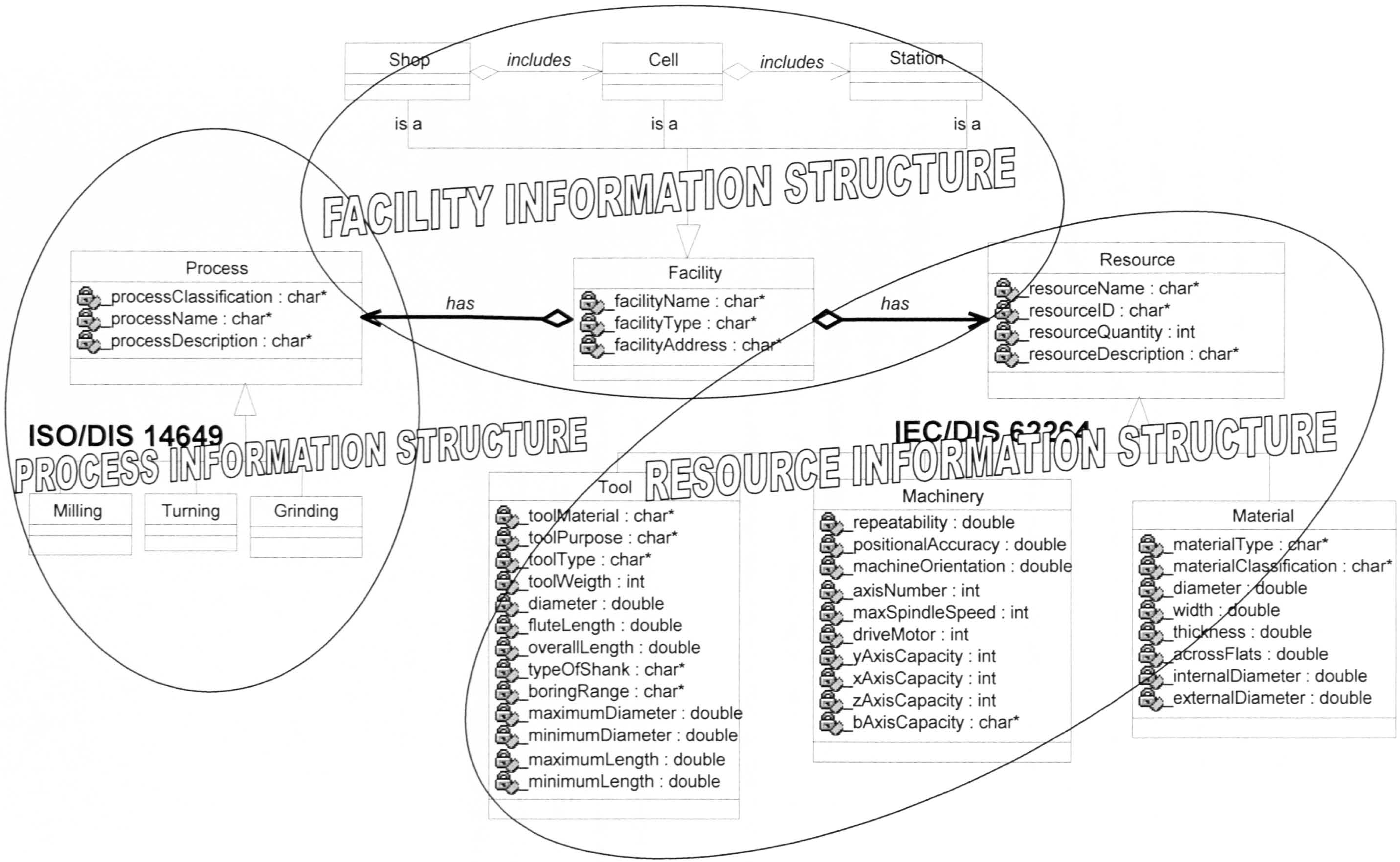


Figure 5-3 Manufacturing Information Structures Relationships

The four kinds of information relationships in a manufacturing facility are based on Molina and Bell's (Molina and Bell 1999) work. However, there is a need to identify the location of the facility information and its relationships analysing the manufacturing information captured in Figure 5-3. The understanding of the facility information locations and relationships enable the information maintenance when new information needs to be added or replaced. The kind of questions that can be answered with these information structures in the decision making process to manufacture a machined part is limited. As a consequence, additional structures to organise the facility knowledge and support the process planning decisions such as process selection or set-ups definitions is required. The facility knowledge and the main relationships are explored in the next section.

5.3.2. Facility knowledge relationships

Facility knowledge explains how the processes and resources in a manufacturing facility can be used. The MFIKM captures the facility knowledge according to three structures: a) process knowledge structure, b) resource knowledge structure, and c) types of knowledge structure. These knowledge structures are depicted in the bottom part of Figure 5-2.

There are four kinds of facility knowledge relationships. Process knowledge, resource knowledge and types of knowledge relationships can be used to organise individually the manufacturing knowledge. The fourth facility knowledge relationship can be used to organise the process and resource knowledge using different types of knowledge representations. These four facility knowledge relationships are explained in the next two paragraphs.

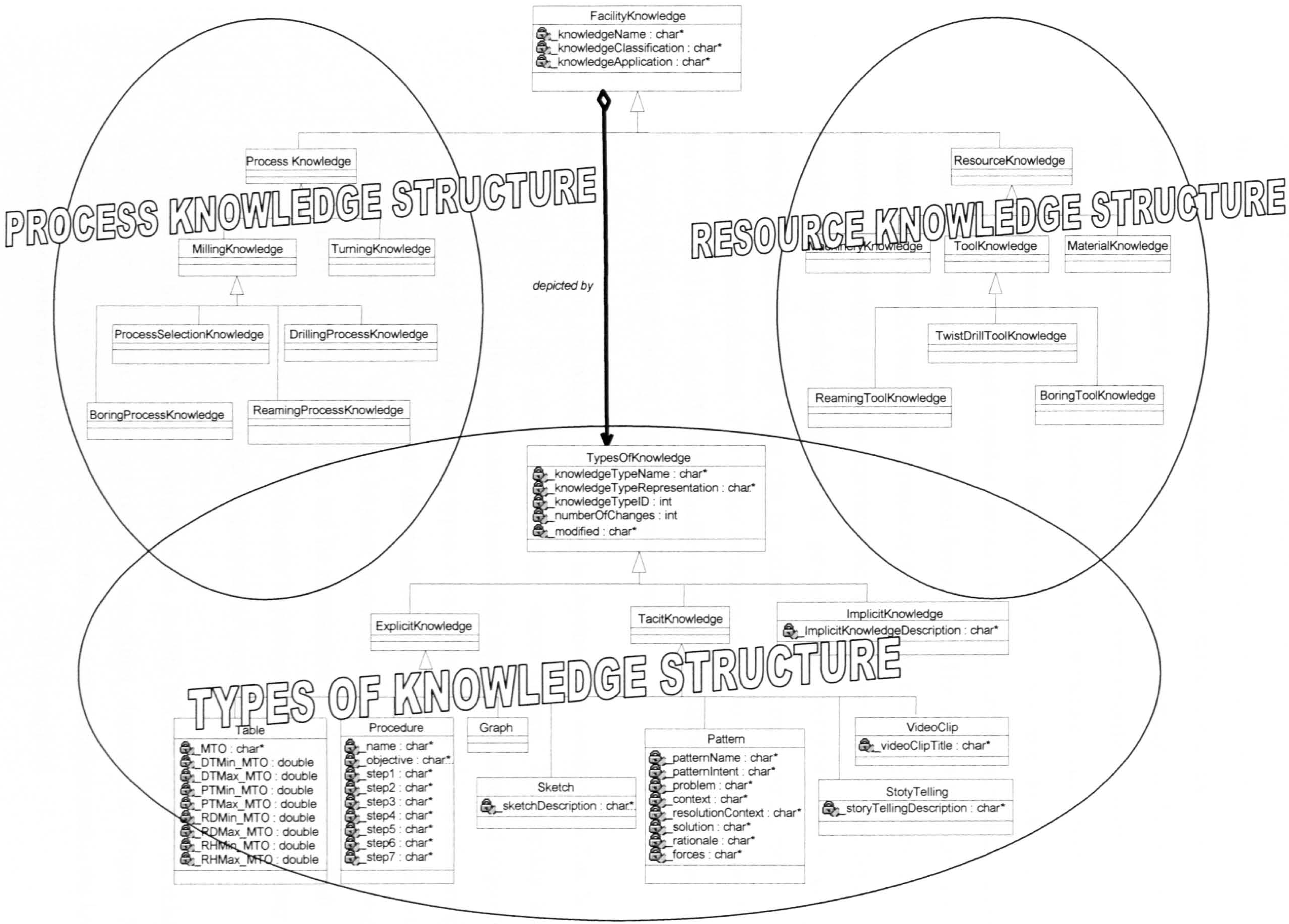


Figure 5-4 Manufacturing Knowledge Structures Relationships

There are three facility knowledge relationships that can be structured individually. The first is the process knowledge relationships that are obtained as a result of the process knowledge structure. The process knowledge structure is used to represent the manufacturing process knowledge needed to manufacture the machined samples presented in chapter 4. As a consequence, process knowledge can be related to milling and turning knowledge. The second is the resource knowledge relationships that are obtained as a result of the resource knowledge structure. The resource knowledge structure is used to represent the manufacturing resource knowledge needed to manufacture the machined samples mentioned. As a consequence, resource knowledge is related to machinery, tool, and material knowledge. The third is the type of knowledge relationships that is obtained as a result of the types of knowledge structure. The type of knowledge structure is used to represent the manufacturing knowledge types needed to organise the knowledge related to process and resource. As a consequence, manufacturing knowledge types can be related to different explicit, tacit and implicit knowledge representations. The circles in Figure 5-4 show the three facility knowledge structures used to explain the three facility knowledge relationships. The next paragraph discusses the fourth facility knowledge relationship.

The fourth facility knowledge relationship is obtained as a result of the link between the *facility knowledge* and *types of knowledge* super classes. This facility knowledge relationship enables the manufacturing knowledge representation related to processes and resources using different knowledge types. As a consequence, the manufacturing process knowledge needed to manufacture the machined samples mentioned can be represented by the use of explicit, tacit and implicit knowledge types. In a similar manner, the manufacturing resource knowledge can be represented by the use of explicit, tacit and implicit knowledge types. This relationship is presented in Figure 5-4 linking how the facility knowledge can be *depicted by* the types of knowledge.

It is possible to identify the location of the facility knowledge and its relationships analysing the manufacturing information structures depicted in Figure 5-4. The understanding of the facility knowledge locations and relationships enable the knowledge maintenance when new knowledge needs to be added or replaced.

5.4. Information and knowledge relationships related to processes and resources

This section argues the information and knowledge relationships related to processes and resources in a manufacturing facility. These relationships are explained using the facility information and facility knowledge related to the machining examples presented in chapter 4. Figure 5-5 depicts example instances related to the facility information and facility knowledge used to support process planning decisions for the round hole manufacture. The instances are linked and organised to support the process selection and set up generation to produce round holes. The example instances have been used to explain the information and knowledge relationships related to processes and resources. These information and knowledge relationships are discussed in the next sections.

5.4.1. Process information and process knowledge relationships

This section discusses the relationships of process information and process knowledge that is used to support the hole making process. A key relationship needs to be made between the milling information instances and the milling knowledge instances to use the information and knowledge combination. This relationship is illustrated in Figure 5-5 using a solid line between the *milling* class and the classes of: *process selection* and *drilling process knowledge*. However, the information and knowledge instances are linked using the UML relationship between the *process* and *facility knowledge* super classes. In the next paragraphs these relationships are explained.

The round hole used as an example utilises the process information and process knowledge relationships to support process planning decisions. Process selection and set up generations are the kinds of process planning decisions to support using these relationships. Figure 5-5 shows with dotted lines the process knowledge classes that process selection (1) and set up generation (2) use. The next discussion is focused on how to combine the process information and knowledge to support these process planning decisions. Combinations of information and knowledge related to milling process are presented. Particularly, process information located in *milling* class and process knowledge located in *process selection* and *drilling process knowledge* classes.

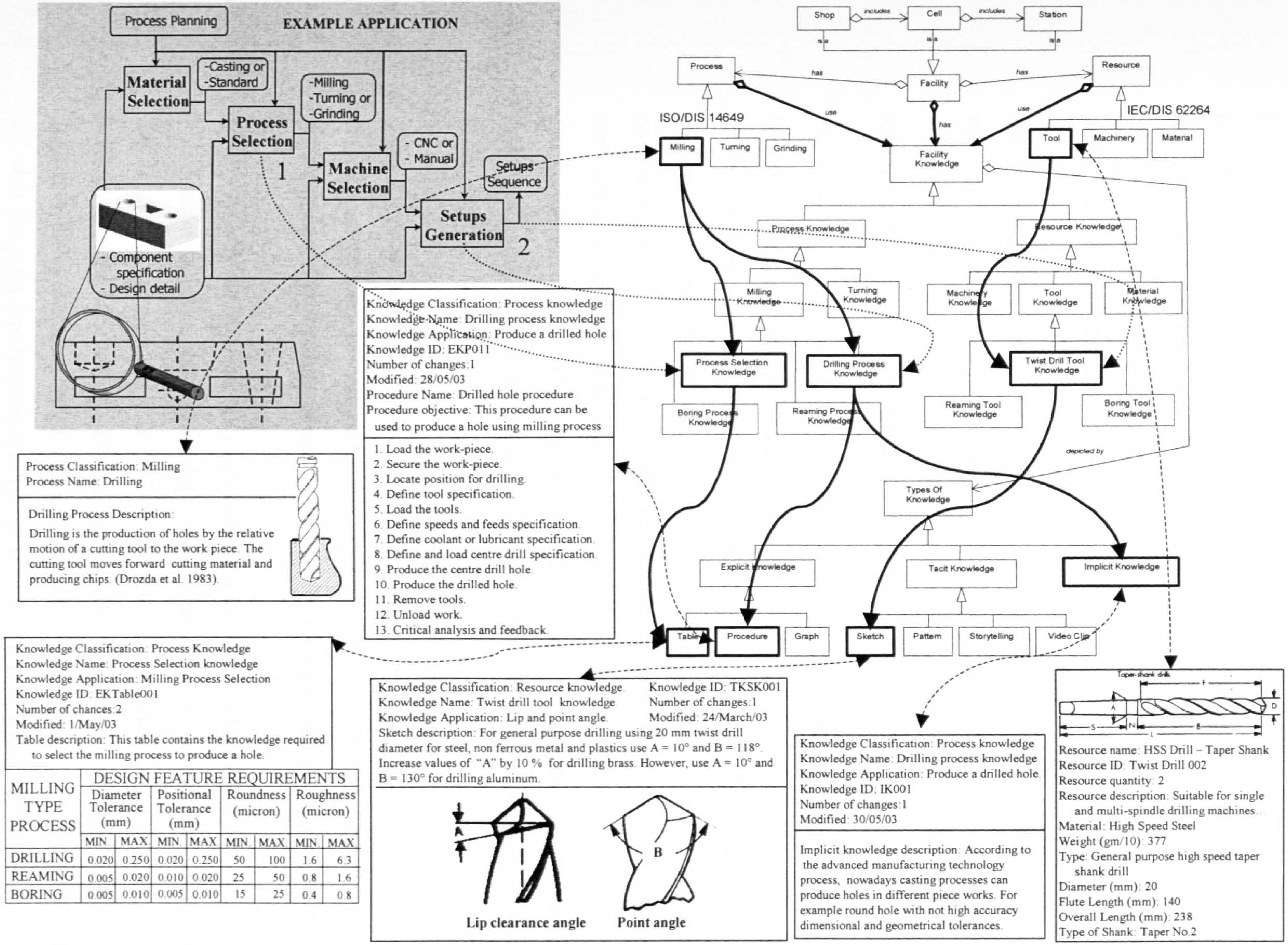


Figure 5-5 Facility information and facility knowledge relationships to produce a round hole

The *process selection knowledge* class organises the process knowledge to support the process selection decision to produce the round hole. Milling knowledge is organised within the *process selection knowledge* class using a table representation. The milling knowledge is structured in a manner that supports a process selection such as drilling, reaming or boring to produce a round hole. The table representation uses the diameter tolerance, positional tolerance, roundness, and roughness hole's attributes to support the decision. This piece of explicit knowledge is processed to provide the suitable milling process to produce a round hole.

The *drilling process knowledge* class organises the process knowledge to support the set up generation decisions to produce the round hole. For example, the combination of drilling process knowledge using a procedure and a piece of implicit knowledge provides useful knowledge to support the set up generation.

The manner by which the process information and process knowledge relationship works is shown when a milling process is selected for the hole making process. A drilling process is considered to explain this relationship. For example, the process knowledge supports the process selection and the set up generation decisions according to a drilling process recommended. However, the process information represented in *milling* class complements these decisions providing useful information related to the drilling process. The instances related to the process information and process knowledge to support the process selection and the set ups generation decisions are represented by the dashed lines in the Figure 5-5.

Using the process information and process knowledge relationship it is possible to obtain the milling process recommended to produce a round hole. Similarly, the process information and process knowledge can be related for each milling process selected.

5.4.2. Resources information and resource knowledge relationships

This section discusses the relationships of resource information and resource knowledge that is used to support the hole making process. A key relationship needs to be made between the tool information instances and the tool knowledge instances in order to use the information and knowledge combination. This relationship is represented in Figure 5-5 with the solid line between the *tool* and *twist drill tool knowledge* classes. However, the information and knowledge instances are linked using the UML relationship between the *resource* and *facility knowledge* super classes. In the next paragraphs the resource information and resource knowledge relationships are explained using a round hole as example.

The tool information and tool knowledge is required in the set up generation to obtain the tool specification to produce a drilled hole. To simplify this example, the diameter and length of the hole are considered sufficient to select a twist drill. In this case, the tool information is processed to provide the suitable twist drill. It is possible to compare the diameter and length of the hole with the diameter and flute length of all twist drills available in the shop stock. According to the relationship mentioned in the above paragraph it is possible to obtain the information and knowledge for the twist drill selected. For example, the twist drill information instance and the sketch knowledge instance depicted in Figure 5-5 can be used to support the tool specification. The tool information and the tool knowledge instances are presented according to the dashed lines in the Figure 5-5.

Summarising section 5.4, It was possible to observe through this machining example that the information and knowledge related to process and resources can be related to support the process selection and the set up generation. The examples discussed have used the experimental software to explore the information and knowledge relationships obtained. This experimental work is presented in the next chapter.

5.5. New facility information and facility knowledge and its relationships

In this section new facility information and new facility knowledge is captured to support the hole making process. The whole information and knowledge organised is used to support process planning decisions such as: process selection and the set up generation to produce a tapered hole. Figure 5-6 depicts the relationships of the new knowledge instances combined with the previous knowledge instances presented in section 5.4. In this case the information and knowledge is organised to produce a tapered hole. Supplementary information and knowledge instances are considered according to the high accuracy required to produce a tapered hole.

The first step in the knowledge maintenance method is to identify the new information and/or knowledge that needs to be updated. To simplify the explanation of this method, information and knowledge related to the turning process is considered as new information and knowledge to support the process planning decisions to produce the tapered hole. According to the knowledge maintenance life cycle presented in chapter 3, section 3.3.2 three sections are explained below: a) information update, b) knowledge update, c) rule criteria update, and d) Relationships related to new information and new knowledge. These four sections are explained below.

5.5.1. Information update

This section discusses how new manufacturing information can be updated in the MFIKM. For this purpose, new turning information is used as an example. The location for the new information is identified following the information structures defined in chapter 4, section 4.3. For example, new facility information related to a shop, cell and station is updated to produce the tapered hole. New resource information related to tools and machinery is as well updated. In addition, new turning information instances are added to support the process selection to produce the tapered hole. It is important to emphasise that, information update is not only the aggregation of new instances according to the manufacturing information structures. Information update can be a minor data change replacing the attribute values for a particular instance already considered. For example, it can be required to modify the resource quantity of the twist drill information presented in Figure 5-5. This can be updated by the current twist drills quantity in the shop stock. One or several of the twist drill attributes can be modified for the same tool information instance. Figure 5-6 put in bold the shop, cell, station, turning and machinery classes representing where the new information instances were added.

5.5.2. Knowledge update

This section discusses how new manufacturing knowledge can be updated in the MFIKM. New turning knowledge is used as an example to show knowledge update. The location for the new knowledge is identified following the knowledge structures defined in chapter 4, section 4.4. Knowledge update is possible because it was identified knowledge structures to add new knowledge.

An important issue here is to decide on the representation for the new knowledge. This decision depends on the best knowledge representation versus the piece of knowledge that needs to be organised. The best representation is the one that avoids loss of valuable knowledge. For example new turning process knowledge is organised to support the process planning decisions to produce the tapered hole. A new procedure is organised as explicit knowledge, a sketch and a pattern are added as tacit knowledge. In addition, a piece of implicit knowledge is considered as well.

It is very difficult to capture a complex piece of knowledge using only a procedure. In these cases a sketch is better than a procedure to capture the complex piece of knowledge. For example, if a procedure is used to capture the knowledge to produce a pilot hole for a tapered hole, the procedure is not sufficient because the sketch represents things that cannot be explained using only a procedure. The combination of a sketch and its description is required to avoid knowledge lost.

Figure 5-6 shows the new knowledge instances that are used to support the set up generation decisions to produce the tapered hole. It is important to emphasise that, knowledge update is not only the aggregation of new knowledge instances according to the manufacturing knowledge structures. Knowledge update can be a minor data and/or information change modifying the attribute for a particular instance already considered. For example, it can be required to modify the sketch description of the sketch instance presented in Figure 5-6. This can be updated by the current know-how. One or several of the sketch attributes can be replaced for the same knowledge instance.

5.5.3. Rule criteria update

This section discusses how the rule criteria can be updated. This is an important point to explain because the knowledge maintenance method considers possible changes in the rule-based criteria. The knowledge maintenance requires the programming modification in addition of the facility information and/or facility knowledge changes. As a consequence, a knowledge relationship can be considered in the combination of programming with the facility information or/and the facility knowledge to support decisions. An example of the rule criteria update is presented below.

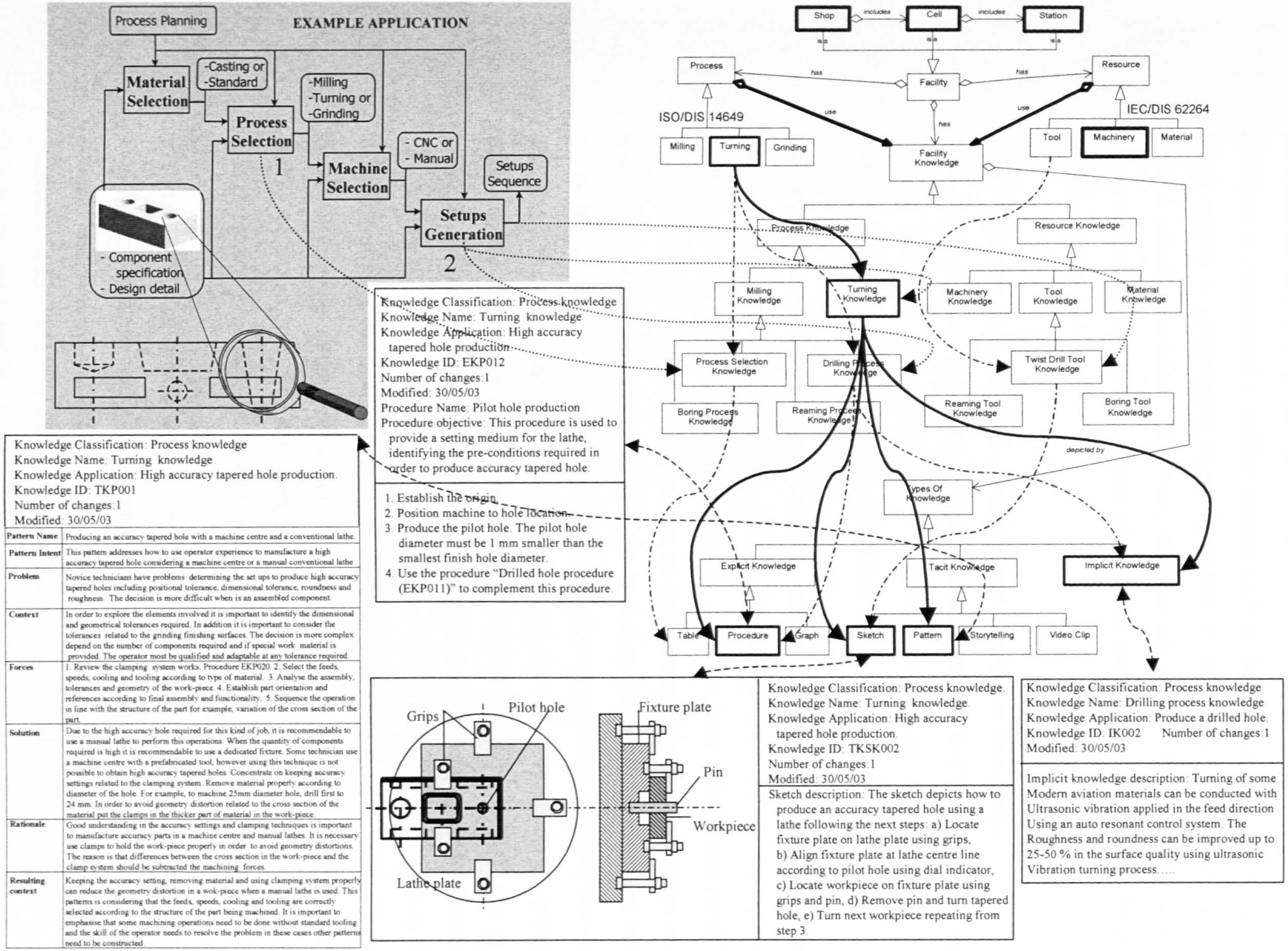


Figure 5-6 New facility knowledge to produce a tapered hole

The table knowledge representation presented in Figure 5-5 is used to support the process selection decision. This piece of explicit knowledge in a table representation considers the diameter tolerance, positional tolerance, roundness, and roughness. These are hole attributes to recommend a milling process such as drilling, reaming or boring. A rule-based criteria is programmed using the values of the hole's attributes to support the process selection decision. However, when an additional hole attribute is required to support this decision the rule criteria needs to be change. This means that the program needs to be changed.

5.5.4. Relationships related to new information and new knowledge

This section discusses how the new facility information and facility knowledge is used to support decisions. Something that is specially emphasised in this section is the knowledge sharing between milling and turning.

Figure 5-6 illustrates the *shop, cell, station, turning* and *machinery* classes emphasising the locating of the new information used to support the decisions for the tapered hole production. This new information is used to show the new information modification within the MFIKM. Figure 5-6 presents, as well, the new facility knowledge instances that can be used to support decisions. These knowledge instances are identified following the dashed lines between the *type of knowledge* subclasses and the instances showed. The previous information and knowledge related to processes and resources are represented following the dashed dot lines in the MFIKM depicted in the Figure 5-6. The previous information and knowledge was used to support the process planning decisions to produce the round hole discussed in section 5.4. However, it is used as well to support the production of the tapered hole. The whole information and knowledge captured can be used following: a) the numbers (1 for process selection and 2 for set ups generation), and b) the dotted lines. The next paragraph considers these numbers and the dotted lines to explore the information and knowledge sharing between milling and turning.

The manufacturing processes can share the whole process knowledge organised in a facility. For example, milling and turning processes are sharing knowledge because the *process* and *facility knowledge* super classes are linked with the UML relationship presented in Figure 5-6. As a consequence, the *turning* and *turning knowledge* classes inherit this relationship. Turning information is located in *turning* class. Similarly, turning knowledge is located in *turning knowledge* class. The turning information and knowledge are related as explained in section 5.4. However, turning knowledge can share the milling knowledge instances using the UML relationship mentioned above. This means that new turning knowledge instances are the instances knowledge following the solid line between the *turning knowledge* class and the classes of: *procedure, sketch pattern* and *implicit knowledge.* However, turning knowledge can share the previous milling knowledge instances captured in the classes of: *process selection knowledge* and *drilling process knowledge.* The previous milling knowledge instances can be identified following the dashed dot lines between classes.

The knowledge organised in the *process selection knowledge* class is used to support the process selection to produce the tapered hole. The process selection is boring as example to produce the tapered hole selected. The information of the boring process is identified in the *turning* class and used as the process overview. To support the set up generation for the tapered hole the turning knowledge and milling knowledge is used. This means that the whole process knowledge instances can be used to support the tapered hole set up generation.

5.6. Summary

This chapter has explored the information and knowledge relationships in the MFIKM to support knowledge maintenance. The facility information and the facility knowledge relationships have been individually investigated to identify the location of the information and knowledge in the MFIKM to enable knowledge maintenance. The combination of information and knowledge related to processes and resources to support process-planning decisions have been presented. The aggregation of new information and new knowledge has been shown exploring the knowledge sharing between milling and turning using updated information and knowledge.

This chapter has presented different examples combining the information and knowledge to support process-planning decisions. These examples use the information and knowledge structures defined and will be validated in chapter 6 using the experimental software developed for this purpose.

CHAPTER 6

6. EXPERIMENTAL SOFTWARE DEVELOPMENT

6.1. Introduction

This chapter explains the development of the experimental software to explore the MFIKM structures to support storage, maintenance, and sharing of manufacturing knowledge.

Five main sections are reported in this chapter. The experimental software design overview is explained in section 6.2. The information and knowledge population into the MFIKM is discussed in section 6.3. New information and knowledge population into the MFIKM is presented in section 6.4. Section 6.5 explains how the information and knowledge stored can be used to support process planning decisions. Section 6.6 discusses the consequence of some knowledge change for process planning decisions.

6.2. Experimental software design overview

6.2.1. General description of the experiments

The experiments performed for this work have been focused on the exploration of the MFIKM structures to test how this model can support storage, maintenance, and sharing of manufacturing knowledge. Four experiments have been performed to explore how the MFIKM can store, maintain updated and share the knowledge to support process planning decisions in the hole manufacture. Information and knowledge for the experiments has been captured from two machining shops at Loughborough University and its technicians. To test the MFIKM structures a set of information and knowledge to produce a round hole and a tapered hole has been defined for implementation purposes. Particularly, this information and knowledge has been organised to support the process planning decisions for the process selection and the set ups generation to produce a round hole and a tapered hole. Basically, the experiments are defined to validate the research arguments specified in chapter 3, 4 and 5. These experiments are described below.

The first experiment explores the use of the structures of the MFIKM as a repository populating information and knowledge to produce a round hole. Two objectives are defined for this experiment, to show the storage of: a) facility information providing different information contexts, b) facility knowledge providing different knowledge contexts. This experiment is presented in detail in section 6.3.

The second experiment explores the use of the MFIKM structures to populate new information and knowledge to produce a tapered hole. The objective for this experiment is to show the implementation of the knowledge maintenance method defined in chapter 3, section 3.3.2, and the MFIKM defined in chapter 4, section 4.5 enabling: a) the manufacturing information maintenance; b) the explicit, tacit and implicit knowledge maintenance. This experiment is presented in detail in section 6.4.

The third experiment explores the use of the MFIKM structures to support the process planning decisions related to process selection and set up generation to produce a round hole and a tapered hole. Three objectives are defined for this experiment showing how the MFIKM supports the process planning decisions using different information and knowledge contexts: a) using current knowledge, b) using updated knowledge, c) sharing knowledge related to processes and resources. This experiment is presented in detail in section 6.5.

The fourth experiment explores changes in the knowledge stored and the changes in the process planning decisions. Two objectives are defined for this experiment to show knowledge changes versus process planning decisions: a) show consequences in the process selection decision changing the process selection knowledge, b) show how a change in the rule based criteria affects the process selection decision. This experiment is presented in detail in section 6.6.

6.2.2. Software development environment

The experimental software development considers two important stages: the software design and the software implementation. The main element pursued in the software design was the exploration of the information and knowledge structures for the MFIKM using UML notation. This is reported in section 6.2.2.1. The main element pursued in the experimental software implementation was the exploration of these structures by the experiments defined in section 6.2.1, using ObjectStore© database and Visual C++©. This is reported in section 6.2.2.2.

6.2.2.1 Object oriented design and analysis for the experimental software

This section discusses the complete MFIKM structures and the product model concept required to obtain the structures for the experimental software developed based on the diagram depicted in Figure 6-1.

The design and analysis of the information and knowledge structures for the MFIKM has been supported by the use of UML notation because as a result of the final model an experimental software application is defined. The software development process provides the rules and discipline to ensure the quality of the software system under development (Quatrani 2003) (Dorador 2001).

The MFIKM discussed in chapter 4, section 4.5 is a short version of the whole system obtained in the present research. Appendix C shows the UML class diagrams for the whole system developed. The short version of the MFIKM presented in chapter 4, is presented with the argument that the objects included in the class diagram are sufficient to show the research ideas related to the storage, maintenance, and sharing of manufacturing knowledge. The information and knowledge structures for the MFIKM were widely explained in chapter 4 using the class diagram concept. In addition, important relationships have been constructed between classes guiding the dynamic aspects of the information and knowledge maintenance. These relationships were widely explained in chapter 5.

The product features categorisation and its characteristics were important in the whole system obtained in the present research. A reason for this is because the product feature characteristics trigger the knowledge organised in a manufacturing facility. The product model contains the information related to the product characteristics, such as, specification, tolerances, geometry and material properties (Young et al. 2001). The author of this thesis has proposed a manufacturing features classification in the product model according to ISO 10303 – 204: 2000 (E). The feature classification has been added in the design for manufacturing view in the product model presented in Appendix C.

Figure 6-1 shows the MFIKM implemented for the experimental software developed. The implementation considers the structures and relationships discussed in chapters 4 and 5, including the product model concept mentioned. The UML class for the whole system considers the link with the product model concept is attached in appendix C. However, to simplify the product model implementation a super class named hole feature is considered in the experimental software representing the product model link. In the software environment the product features are considered as products. This hole feature super class can be identified in Figure 6-1.

6.2.2.2 Object oriented programming of the experimental software.

Figure 6-1 presents the experimental system implementation using the object-oriented database ObjectStore©. The functionality of the software application was programmed using Microsoft Visual C++© to carry out the four experiments defined in section 6.2.1. The visualisation of the results has been realised by the output dialogues of the experimental software application developed.

The following software tools have been applied in the experimental software development: A) ObjectStore Designer to design the object-oriented database including the classes, data members, methods and relationships. The Component Wizard was used to generate MFC applications (ObjectStore 2003). B) Visual C++ 6.0 programming language to implement the application using the code created by the Component Wizard (Gosselin 2001). C) Object-oriented database management system ObjectStore SP8.0 allowing the data management within the database (ObjectStore 2003). D) ObjectStore Inspector as a graphical tool to browse, edit, query, and report on the data in an ObjectStore database (ObjectStore 2003). Additional concepts related to the software tools applied to support the design and implementation of the experimental software were discussed in chapters I and II, and extended in appendix A.

At the end of section 6.2 can be summarised that a deep object oriented analysis and design was carried out to obtain MFIKM structure presented in Figure 6-1. Based on these final structures, an experimental software application was defined and four experiments will be performed to validate storage, maintenance, and sharing of manufacturing knowledge. In the next sections the experiments are explained using the experimental software developed.

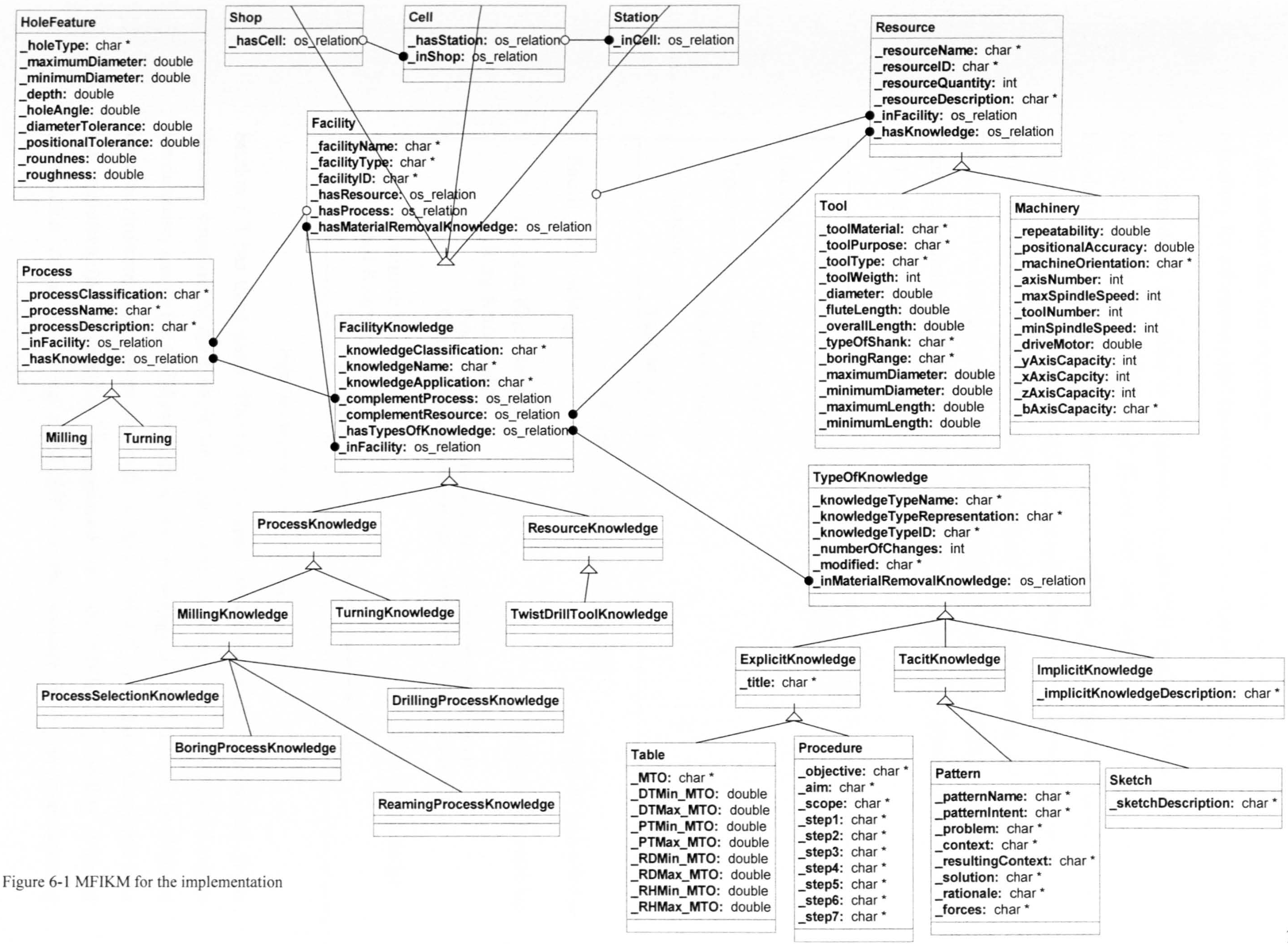


Figure 6-1 MFIKM for the implementation

6.3. Information and knowledge population into the MFIKM

In this section the first experiment aims to confirm the use of the model structures as a repository for information and knowledge related to a manufacturing facility.

It is considered that there is no previous information and knowledge stored in the MFIKM. Figure 6-2 identifies the classes that will store the first information and knowledge into the model. It is important to emphasise that the facility information is structured combining facility, process and resource information. In a similar manner, the facility knowledge is structured combining facility knowledge using knowledge types. The information and knowledge contexts are obtained as a result of these combinations. Examples of facility information and knowledge are respectively presented in sections 6.3.1 and 6.3.2.

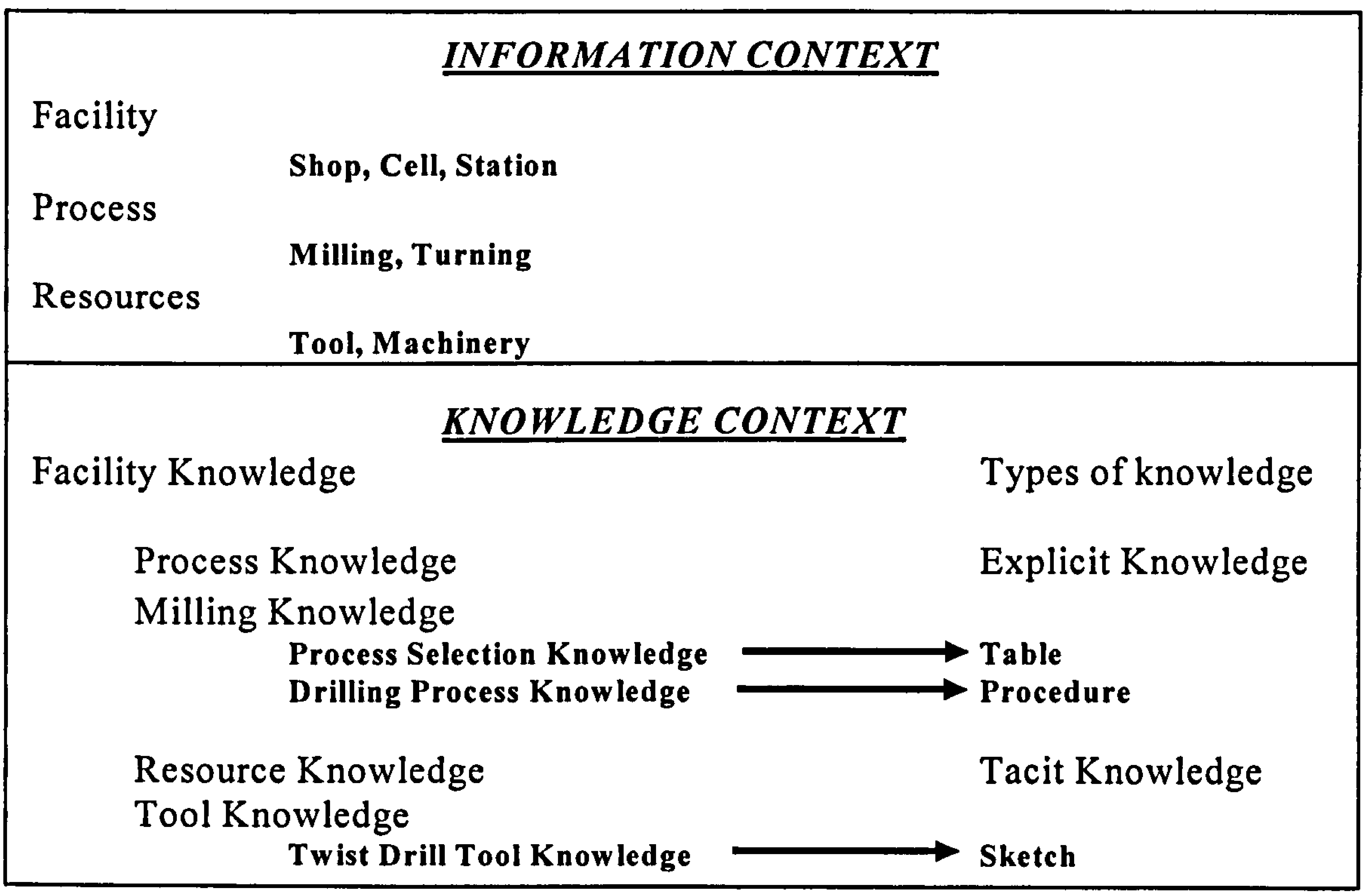


Figure 6-2 Information and Knowledge Considered

Section 6.3 has three parts. The two first parts discusses mainly three points: a) the database structure, b) the kind of information and knowledge that can be stored within the database, and c) the useful information and knowledge contexts that can be obtained with the structure relationships. According to this, section 6.3.1 explains the manner how the manufacturing information is populated into the MFIKM providing different information contexts. Section 6.3.2 explains the manner how the manufacturing knowledge is populated into the MFIKM providing different knowledge contexts. Finally, section 6.3.3 summarises the first experiment results.

6.3.1. Manufacturing information population

Figure 6-3 represents the detailed information structure for the implementation showing the relationships and attributes considered in the experimental software to store the facility information into the ObjectStore database.

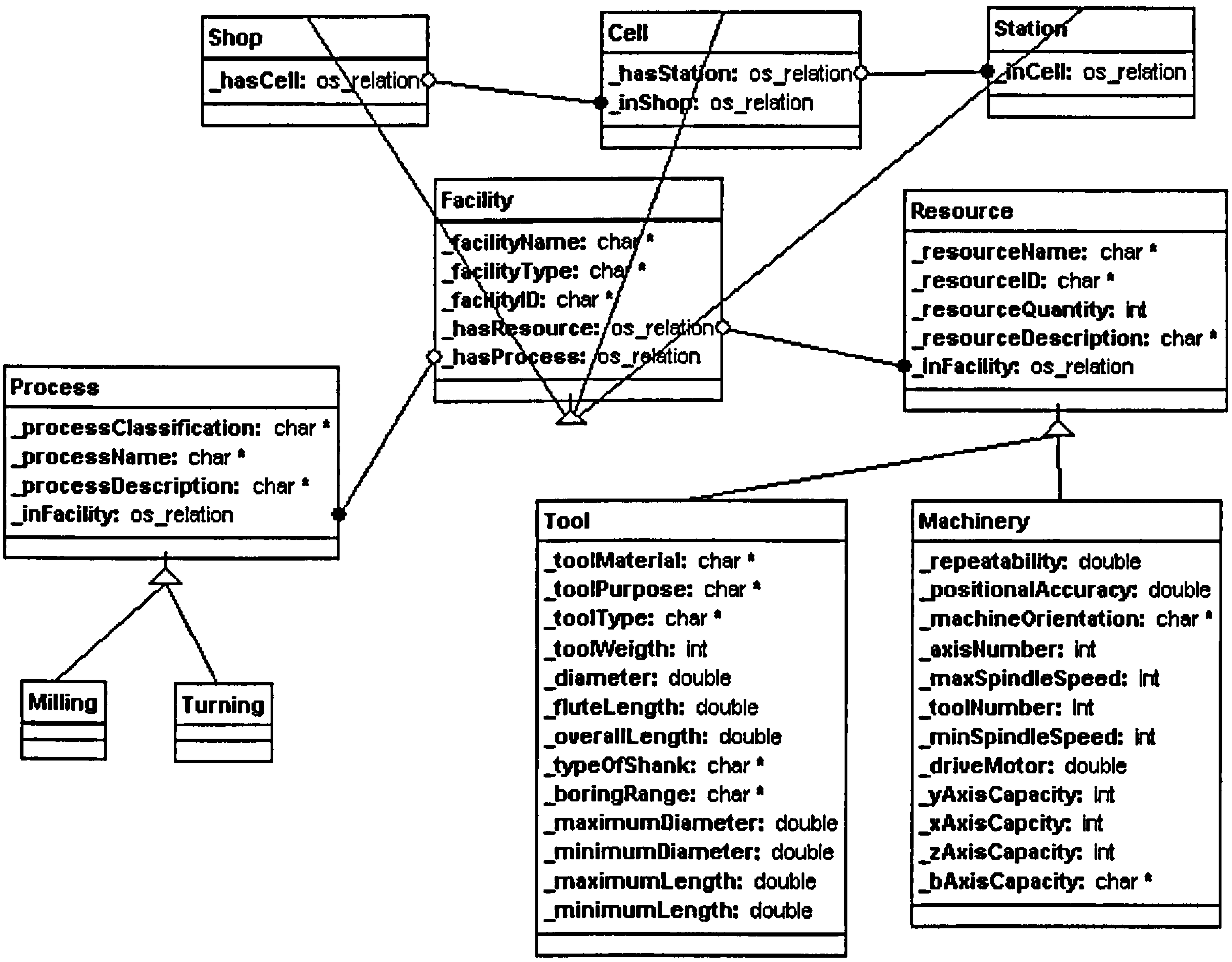


Figure 6-3 Detailed manufacturing information structure implemented

The main classes selected to store the facility information are: *shop, cell,* and *station* classes related to the *facility* super class. In similar manner, *milling* and *turning* classes for *process* super class, and *tool* and *machinery* classes for *resource* super class. These classes are mentioned in the upper part of Figure 6-2 emphasising the facility information considered within the database. The information instances stored within the database are according to each specific super class attributes and the respectively child class attributes. These attributes can be observed in Figure 6-3. Then, the kinds of information stored within the database are information instances related to a) shops, cells, and stations facilities; b) turning and milling processes; c) tools and machinery resources. The population of some of these instances are presented in the next paragraphs using the experimental software.

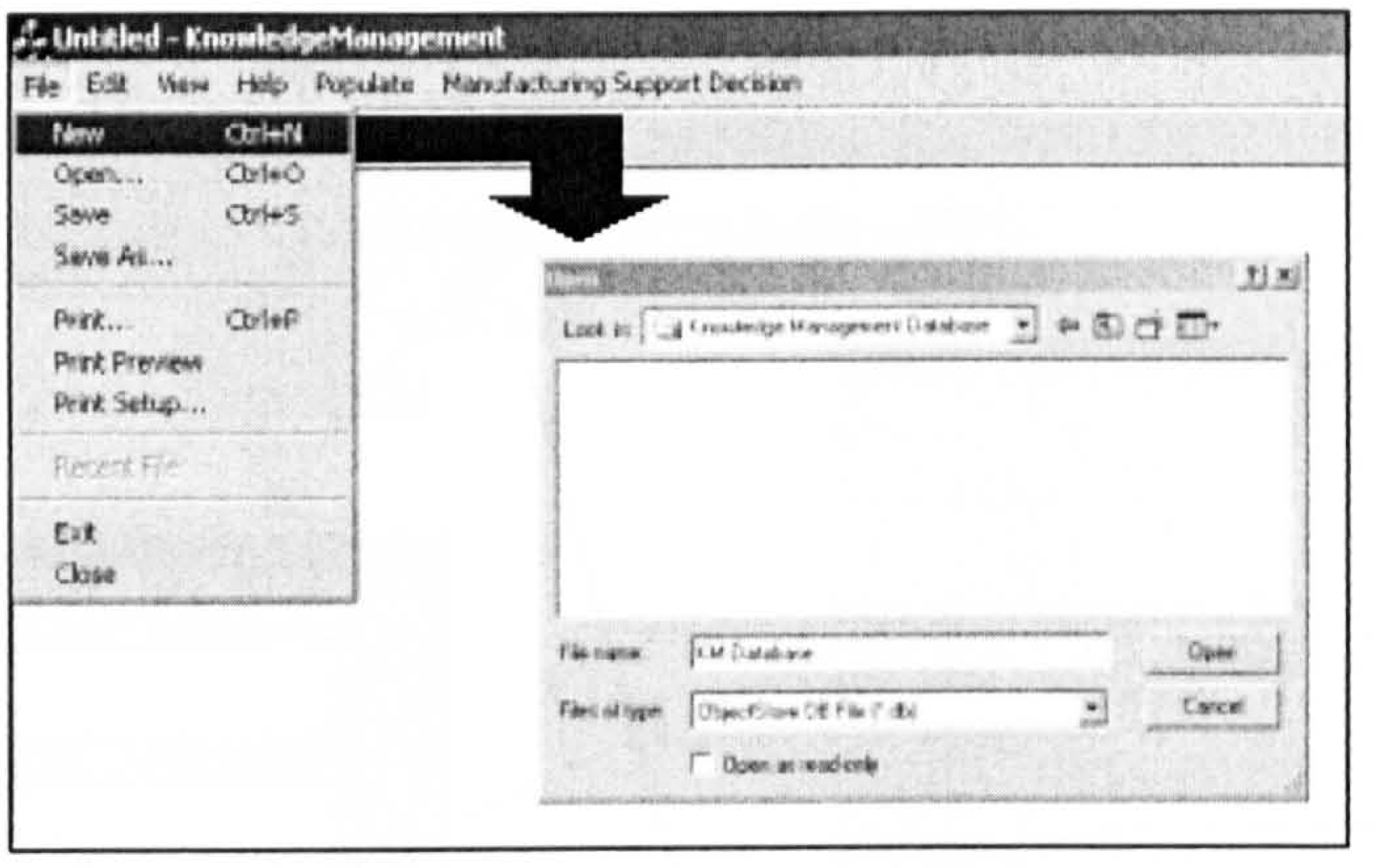


Figure 6-4 Creating a New MFIKM

The creation of a new MFIKM database is required to store the facility information. According to the main menu in the experimental system this can be done by click on "new" and select the location to save the database file in the computer. Figure 6-4 shows the dialog box in which is represented how to create a new MFIKM database.

Figure 6-5 shows the dialog boxes in which facility information is entered. For example, instances related to shops, cells and stations are stored within the database according to name, type and ID attributes. In a similar manner, information instances related to a) resources (i.e. tools and machineries), and b) processes (i.e. milling and turning) are stored within the database. These resources and processes instances are populated according to the attributes presented in Figure 6-3. Appendix D shows the dialog boxes in which information related to processes and resource is entered.

The information relationships are important in the facility information populated. For example, a station or group of stations are included in specific cells, a cell or group of cells are included in particular shops. These relationships are represented in Figure 6-3 connecting station, cell and shop classes to each other. The relationships were implemented in the dialog boxes presented in Figure 6-5. For a new cell is required to select a particular shop and for a new station is required to select a particular cell. The dashed lines represent the interconnection instances.

Facilities, processes and resources have two important information relationships. In this case, a facility has processes and resources. Then, a particular facility instance has specific processes and resources. These relationships are represented in Figure 6-3 connecting a) *facility* and *process* super classes, and b) *facility* and *resource* super classes. In a similar manner such as shops, cells and stations population, the relationships were implemented in the dialog boxes presented in the in appendix D.

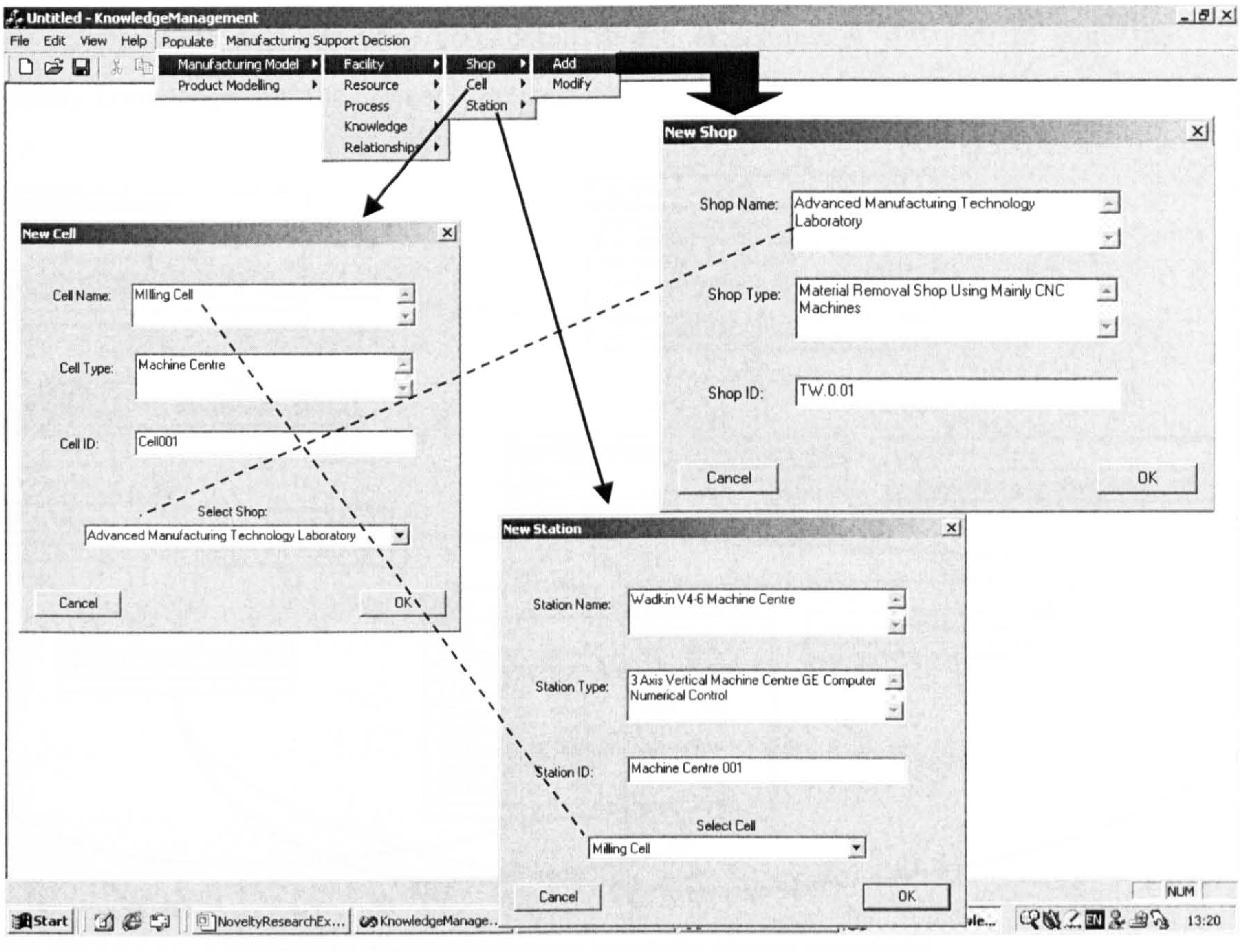


Figure 6-5 Facility information population into the MFIK

Different information contexts can be obtained following the relationships between facilities, processes and resources. The shops, cells and stations can be associated each other and related with the whole processes and resources populated. For example, each facility shop can be related with specific cells and stations. This is a particular information context where the information organised has a meaning. In addition, the process and resources can be related with the specific shops that belong to. These are additional information contexts and each one has a particular meaning.

Manufacturing facility information organising shops, cells, and stations with particular processes and resources were identified in this section providing different information contexts with particular meaning. However, facility knowledge explains how the processes and resources in a manufacturing facility can be used, and this is explained in the next section.

6.3.2. Manufacturing knowledge population.

Figure 6-6 represents the detailed knowledge structure for the implementation showing the relationships and attributes considered in the experimental software to store the facility knowledge into the ObjectStore database.

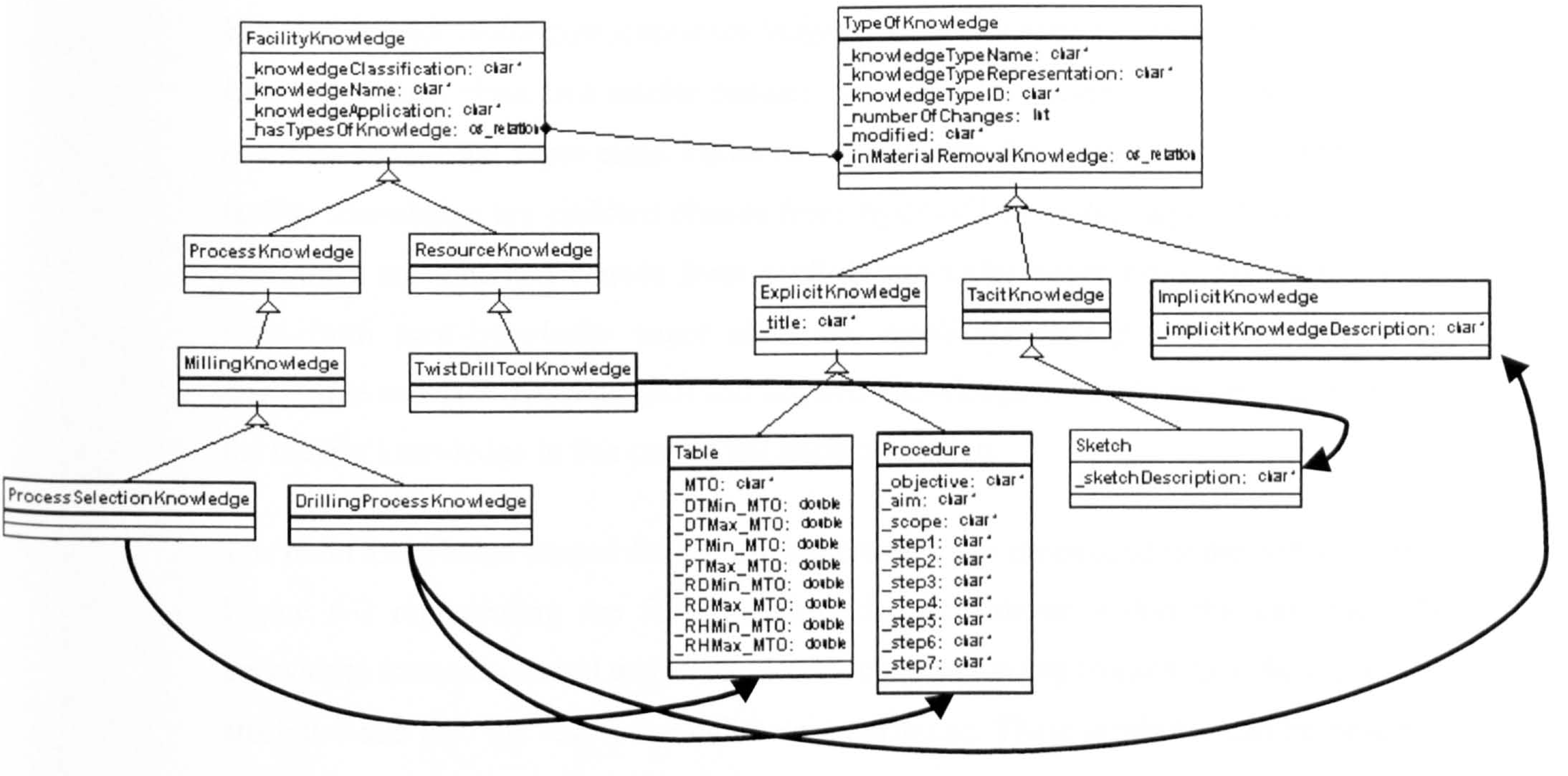


Figure 6-6 Detailed manufacturing knowledge structure implemented

Two main classes are used to implement manufacturing facility knowledge named *facility-knowledge* super class and *types-of-knowledge* supper class. These two classes implemented are presented in Figure 6-6 and discussed in the next paragraphs.

The *facility-knowledge* super class contains the knowledge for the manufacturing facility. Two main categorisations were implemented named *process-knowledge* and *resource-knowledge*. The whole process knowledge captured is implemented in the *process-knowledge* categorisation. In a similar manner, the whole resource knowledge captured is implemented in the *resource-knowledge* categorisation. The knowledge categorisation can be as wide as the knowledge captured within the manufacturing facility. Figure 6-6 represents the classes implemented, however additional facility knowledge categorisations can be observed in Figure 4-5 and in the diagram presented in appendix C.

The *types-of-knowledge* super class implements the knowledge types used to represent the facility knowledge. There is a significant relationship between the two super classes that enable the knowledge representation. The relationship is *facility-knowledge* **has** *types-of-knowledge*. The structure for knowledge types was widely explained in chapter 4, section 4.4.1 However the main classes implemented according to Figure 6-6 are mentioned below.

The main classes selected to store the facility knowledge are: *process-selection-knowledge* and *drilling-process-knowledge* that are inherited classes from *process-knowledge* super class. In a similar manner, *twist-drill-knowledge* class is a subclass from *resource-knowledge* super class. However, in this case the classes used to represent the facility knowledge are children classes from *types-of-knowledge* super class. *Table* and *procedure* are inherited classes from *explicit-knowledge* super class. *Sketch* is a child class from *tacit-knowledge* super class and *implicit-knowledge* class is a *types-of-knowledge* subclass. Explicit, tacit and implicit knowledge concepts are used to represent the facility knowledge in this part of the implementation.

The main knowledge classes for the implementation are mentioned in the bottom part of Figure 6-2 representing the facility knowledge considered within the database. The knowledge instances stored within the database are according to each specific super class attributes and also the respective child class attributes. These attributes can be observed in Figure 6-6. Then, the kinds of knowledge stored within the database are knowledge instances related to process selection, drilling process and twist drill tool. In the next paragraphs are presented the population of some of these instances.

The same database created to populate facility information is now used to populate facility knowledge. According to Figure 6-6 four *facility-knowledge* instances were stored. However, due to the similarity of the population only two instances of *drilling-process-knowledge* are presented in Figure 6-7 and used as example. The *facility-knowledge* instances populated for *process-selection-knowledge* and *twist-drill-knowledge* are included in appendix D.

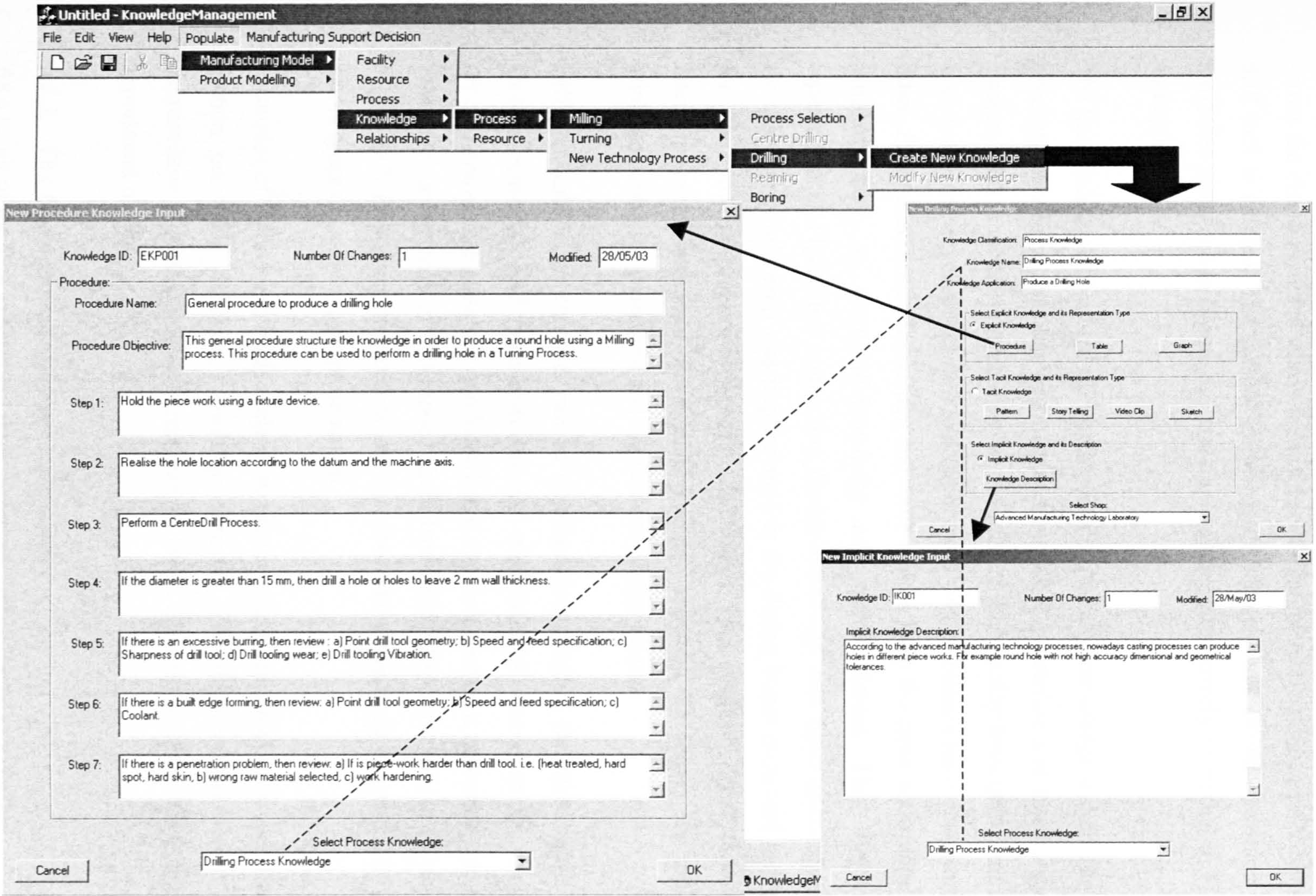


Figure 6-7 Drilling process knowledge population into MFIKM.

Figure 6-7 shows the dialog boxes in which the two *drilling-process-knowledge* instances are entered. For example, the drilling process knowledge is stored within the database as procedure and implicit knowledge instances. In a similar manner, appendix D shows the dialog boxes in which facility knowledge related to process selection and twist drill tool is entered. The facility knowledge instances were stored consistent with the attributes presented in Figure 6-6 and implemented respectively according to Figure 6-7 and appendix D.

The knowledge relationships are important in the facility knowledge stored. The *drilling-process-knowledge* class has two instances stored in *procedure* and *implicit-knowledge* classes. This is possible according to the relationship *facility-knowledge* **has** *types-of-knowledge*. However, *procedure* and *implicit-knowledge* classes have one instance each other. *Process-selection-knowledge* and *table* classes have the same knowledge instance Similarly such as *twist-drill-knowledge* and *sketch* classes. This relationship is represented in Figure 6-6 connecting *facility-knowledge* and *types-of-knowledge* super classes. The relationship was implemented in the dialog boxes presented in Figure 6-7 for the *drilling-process-knowledge* instances. The dashed lines represent the interconnection instances. In similar manner, appendix D shows the relationship implementation for *procedure* and *implicit-knowledge* classes.

Different knowledge contexts can be obtained according to the relationship between *facility-knowledge* and *types-of-knowledge* super classes. For example, the *drilling-process-knowledge* class has two knowledge contexts: one as a procedure and the other as implicit knowledge in text mode. These two knowledge contexts can be observed in Figure 6-7. However, the process and resource knowledge can be associated with the whole types of knowledge representation.

Examples of facility knowledge related to processes and resources were identified in this section providing different knowledge contexts. The different knowledge contexts support how processes and resources can be used. The next section summarise the first experiment results.

6.3.3. The Evaluation of the First experiment

As a result of the first experiment three important issues can be emphasised.

1) MFIKM enables storage of meaningful manufacturing information contexts providing a facility overview.

2) MFIKM enables storage of useful manufacturing knowledge contexts to support how processes and resources can be used.

3) The information and knowledge structures created for the MFIKM enables the storage of specific information and knowledge related to resources and processes in a manufacturing facility.

The first experiment has shown how the MFIKM stores information and knowledge instances. The next step is to show how new instances can be stored. This is presented in the next section.

6.4. New information and knowledge population into the MFIKM

In this section the second experiment aims to confirm the use of the model structures as a repository for new information and knowledge related to a manufacturing facility.

This section has three parts. The first part is focused on information maintenance. The second part is focused on knowledge maintenance. Finally, the third part presents the experimental results.

6.4.1. Manufacturing information maintenance

As previously presented in section 6.3.1 some information instances were stored within the MFIKM. This section uses the same information structure depicted in Figure 6-3 and explains how new information instances can be added or replaced.

As previously described in chapter 3, section 3.3.2, a knowledge maintenance method was created to support the information and knowledge maintenance. Figure 6-8 represents the information maintenance life cycles. Basically, this cycle consists of the new information identification, the new information location in the MFIKM structure and the action of information update. This cycle was implemented updating information related to facilities, processes and resources instances within the MFIKM.

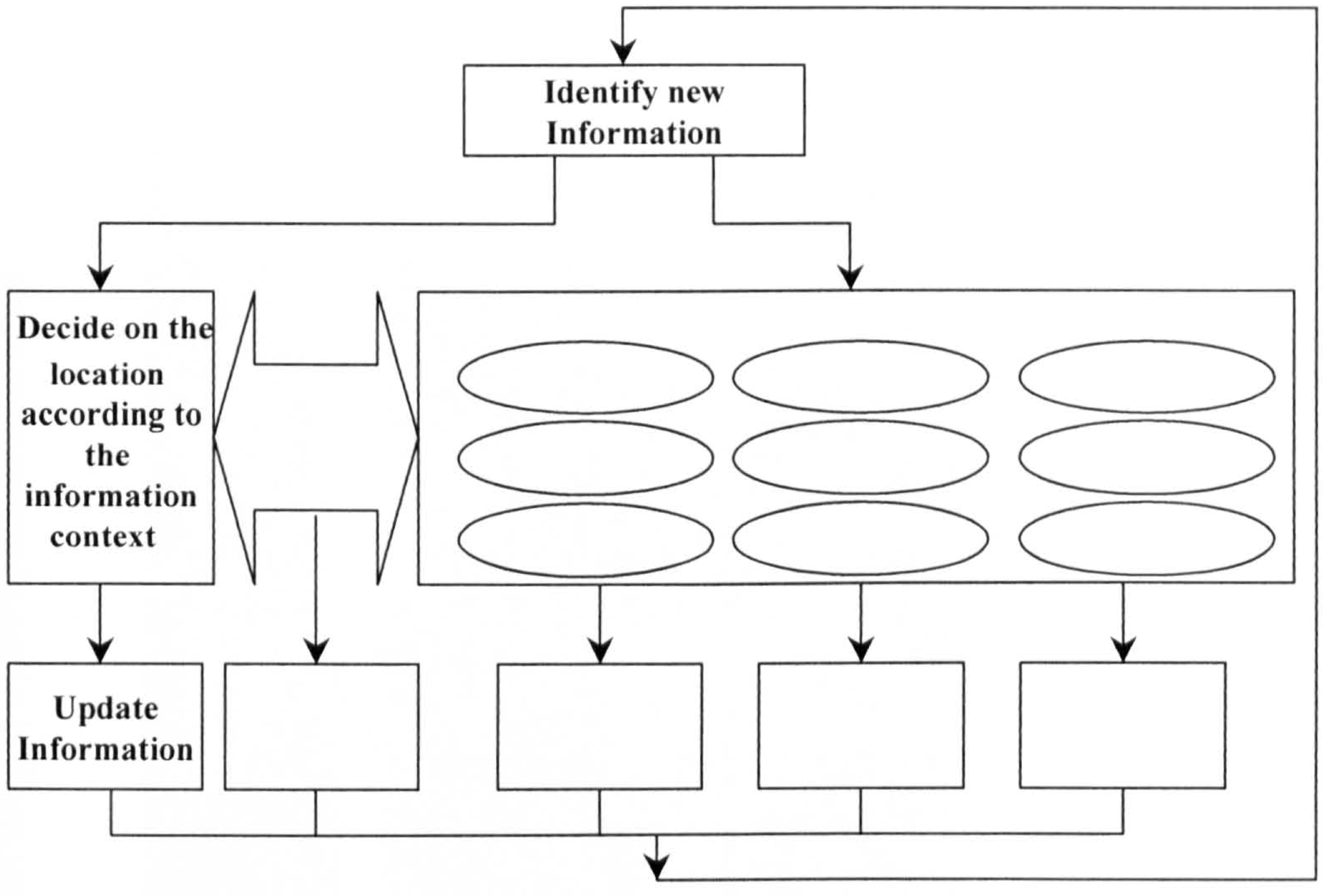


Figure 6-8 Information maintenance life cycles.

The information maintenance life cycle starts with the new information identification. The new information identification is related to facilities, resources and processes to simplify the information update. Figure 6-9 shows the dialog boxes in which new resource information is located and updated. In a similar manner, appendix D shows the dialog boxes in which new information related to facilities and processes is located and updated.

The existing resources instances stored into the MFIKM database can be observed in Figure 6-9 as an example. Machinery and tools instances that were stored previously can be located within the database. Figure 6-9 shows the attributes for a Harrison 400 lathe and a boring bar according to the information structure defined. The information update can be done in three manners: a) edit the information from the database and update the attributes defined for a particular instance, b) add new resource instances, and c) delete instances already stored. Figure 6-9 represents the maintenance of resource information in MFIKM, appendix D represent in similar manner for facilities and processes.

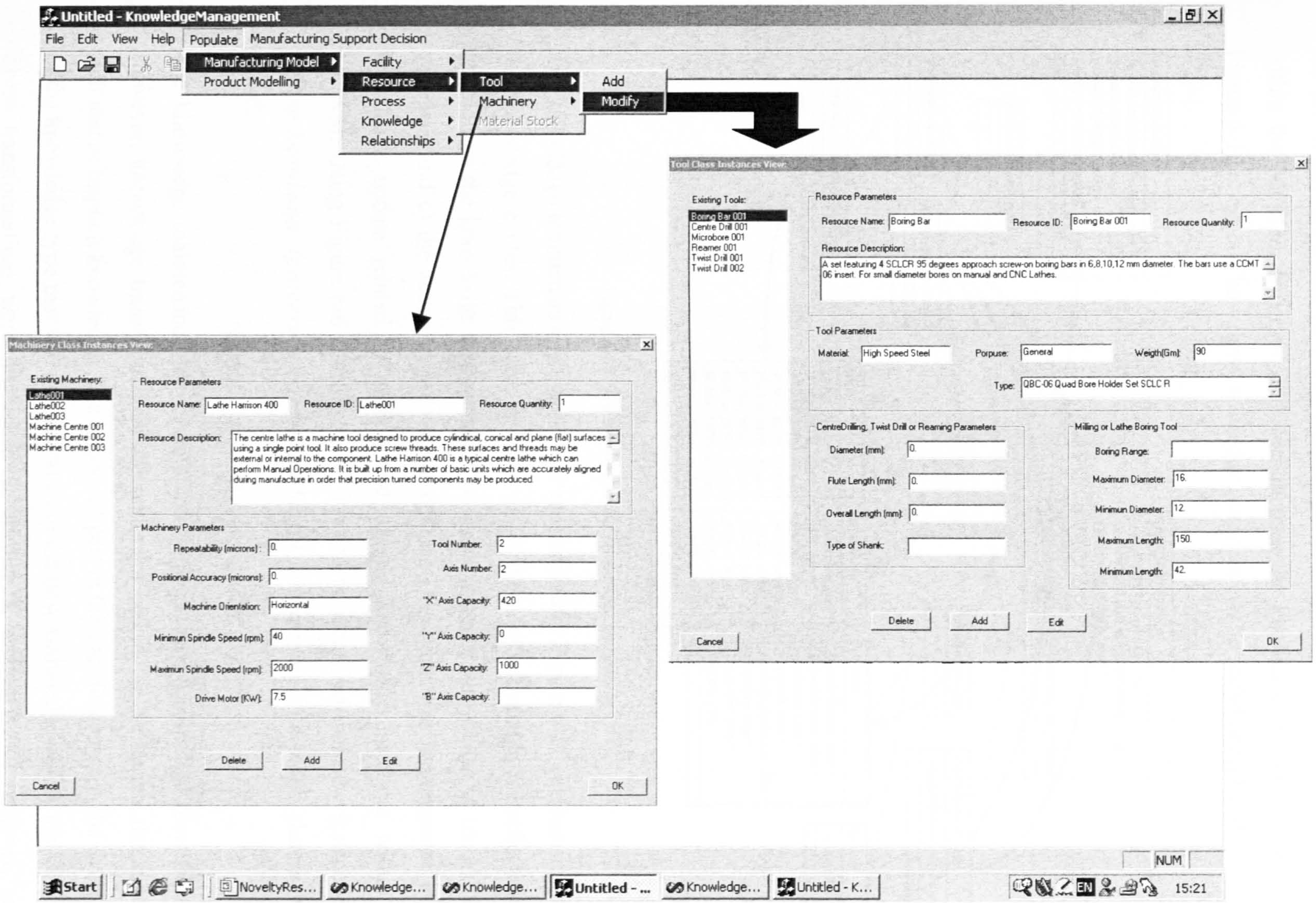


Figure 6-9 Maintenance of resource instance information in MFIKM.

6.4.2. Manufacturing knowledge maintenance

As previously presented in section 6.3.2 different knowledge instances were stored within the MFIKM. However, this section uses the knowledge structure depicted in Figure 6-10 to explain how new knowledge instances can be added or replaced.

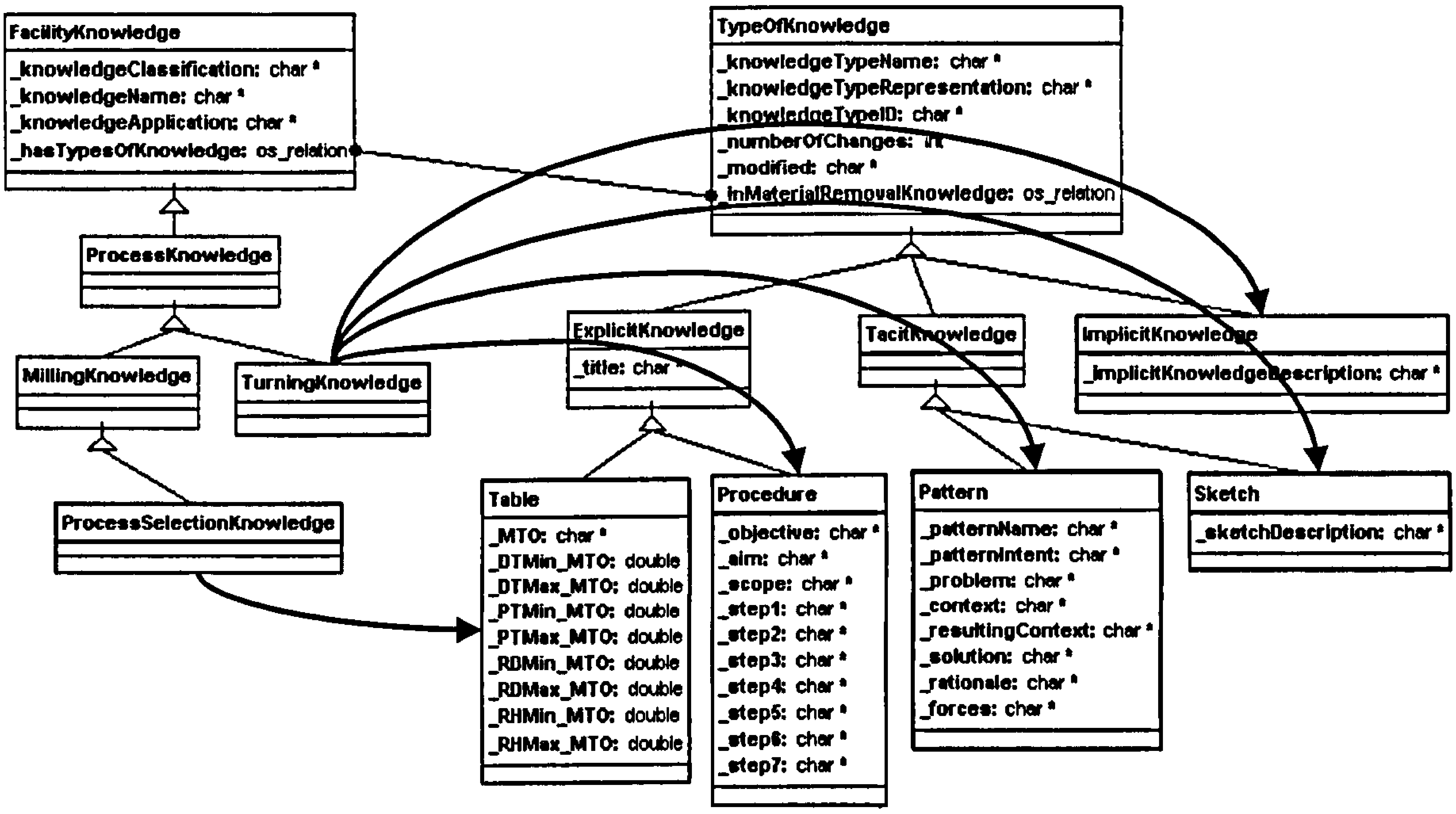


Figure 6-10 New manufacturing knowledge population

The knowledge maintenance life cycles are represented in Figure 6-11 emphasising only the knowledge cycles. This cycle consists of: a) the new knowledge identification, b) decision on the knowledge representation to locate the new knowledge in the MFIKM structure, and c) the action of knowledge update. This cycle was implemented in the knowledge update related to milling and turning knowledge instances within the MFIKM. Using Figure 6-6 and Figure 6-10 it can be identified that new instances for *milling-knowledge (process-selection-knowledge)* and *turning-knowledge* classes were added.

The knowledge maintenance life cycle starts with the new knowledge identification. However, knowledge transformations are important before this to update the explicit, tacit and/or implicit knowledge. The important part in the transformation is the definition of the knowledge type that will be used to store the new knowledge within the MFIKM. These transformations were mentioned in chapter 3, section 3.3.2; however, some examples are presented in this section.

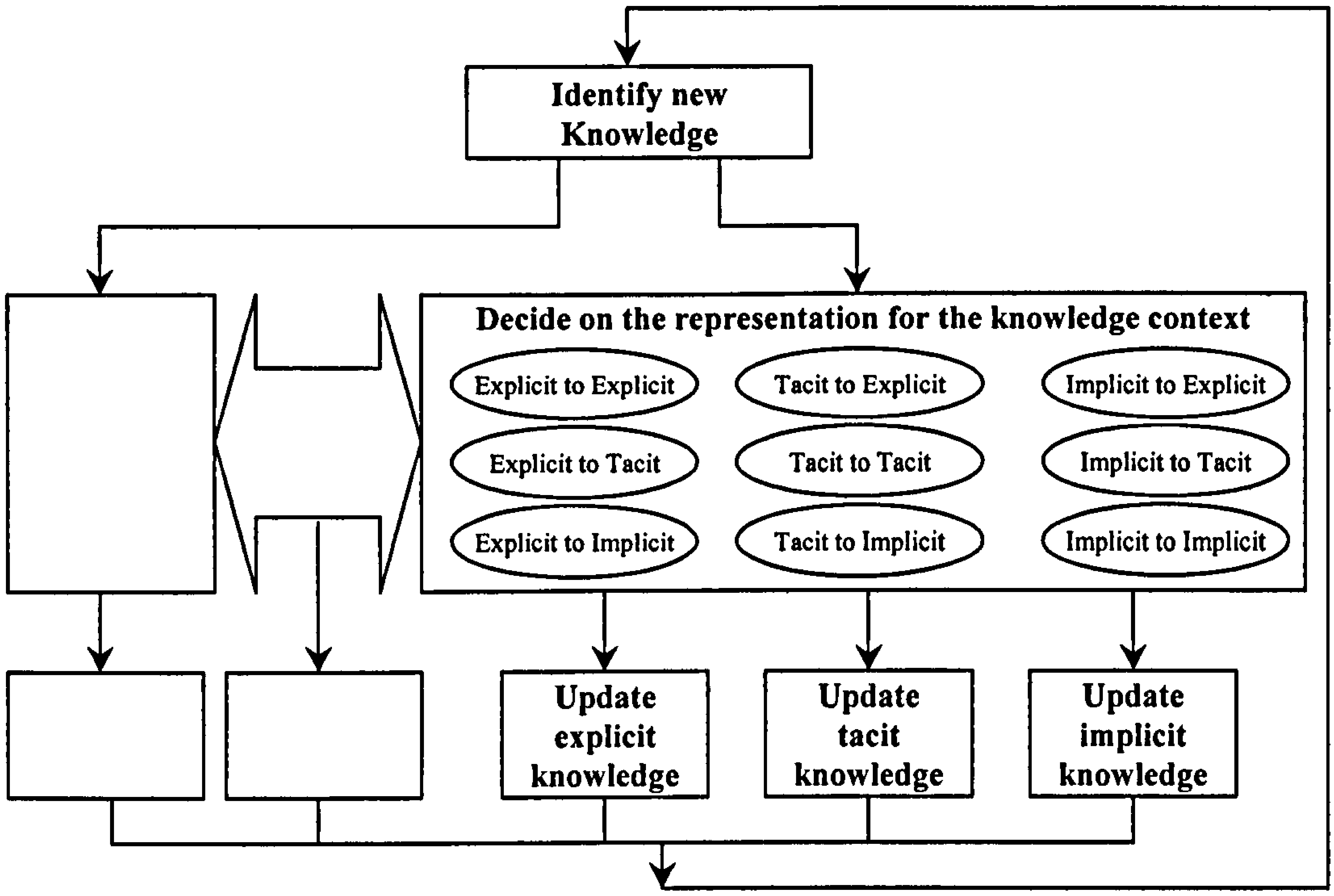


Figure 6-11 Knowledge maintenance life cycles

New knowledge is created and/or discovered in a manufacturing facility daily. Figure 6-10 represents a facility knowledge structure that can store new process knowledge. However an important point is to decide on the representation for the new knowledge avoiding the key new knowledge loss. Figure 6-12 depicts the manufacturing explicit, tacit and implicit knowledge conceptual link. This figure is used to explain the type of knowledge decisions. An explanation is presented next.

Explicit and tacit knowledge have been used in this research to capture tested manufacturing knowledge. In other words, explicit or tacit knowledge is used if the new knowledge is well-known knowledge and has been applied with good results. For example, the piece of explicit knowledge represented in a procedure in Figure 6-7 is well-known knowledge because is a tested drilling knowledge to drill a hole. Implicit knowledge has been used in this research to capture new manufacturing technology knowledge. New technology knowledge is the related to manufacturing knowledge that not has been fully tested. The new casting and ultrasonic vibration turning technologies to produce holes can be examples. Based on the differences between manufacturing explicit, tacit and implicit knowledge explained. The knowledge representation decision is the representation that avoids the new knowledge loss for each knowledge type.

According to the knowledge representation used there is a clear difference between the manufacturing explicit and tacit knowledge, although both are used to capture tested knowledge. However, between manufacturing tacit and implicit knowledge can be confused. Particularly between a story telling and a piece of implicit knowledge. However, a difference between implicit and tacit knowledge is that tacit knowledge follows a particular format and uses tested knowledge. On the other hand, implicit knowledge is only a text message related to new technology knowledge.

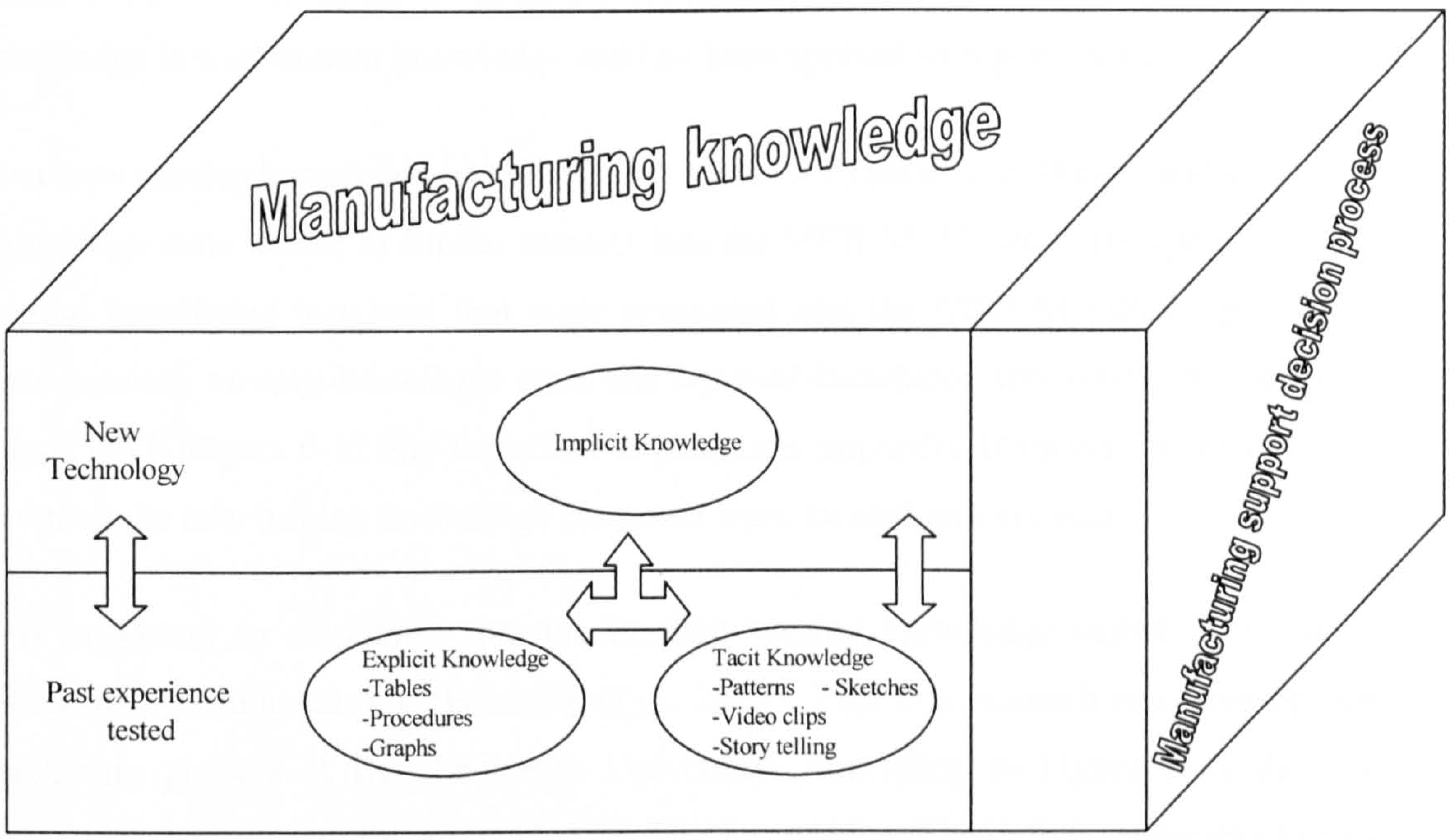


Figure 6-12 Manufacturing types of knowledge integration

Figure 6-12 and the above explanation provides a good overview about manufacturing knowledge maintenance and can be observed that new facility knowledge can be updated using explicit, tacit and implicit knowledge concepts to support manufacturing decisions. Combining Figure 6-10, Figure 6-11 and Figure 6-12 an example of explicit to explicit transformation in the knowledge maintenance life cycle is provided next.

As previously presented in section 6.3.2 *process-selection-knowledge* was populated into the MFIKM using a *table* knowledge representation. Appendix D shows the dialog boxes in which the *process-selection-knowledge* instance provides the knowledge required to define a drilling process to produce a round hole. Using this explicit knowledge idea for drilling, two additional instances were added to define a reaming and boring processes to produce a round hole. In this case the transformation was explicit to explicit. A detailed explanation of this transformation is presented in the next paragraph.

A reaming and boring piece of new knowledge was identified for *process-selection-knowledge* class. This is the first step according to Figure 6-11 and explicit to explicit transformation was done following the drilling previous example. The arrow depicted in Figure 6-10 linking *process-selection-knowledge* and *table* classes represent the population of the new two instances. Figure 6-13 shows the dialog boxes in which the new process selection knowledge is located and updated. According to Figure 6-12 it can be observed that explicit knowledge for the new *process-selection-knowledge* is correct because it is structuring the reaming and boring that are conventional processes. The new knowledge is well-known knowledge and has been applied with good results.

Four new turning knowledge instances: a) procedure, b) pattern, c) sketch, and d) implicit knowledge were stored in similar manner into the MFIKM. Figure 6-10 represents these turning knowledge instances that were populated into the MFIKM following the bold lines between *turning-knowledge* class and *types-of-knowledge* subclasses. According to Figure 6-11, Figure 6-12 and the above explanation, appendix D shows the dialog boxes in which the new turning knowledge instances were located and updated.

It is important to emphasise that the implicit turning knowledge stored is related to ultrasonic vibration turning (Babitsky et al. 2003). This is a research and development machining process at Loughborough University. According to Figure 6-12 the new knowledge related with this process is implicit knowledge. The definition for this turning process and the implicit knowledge was presented in appendix D.

At the end of section 6.4.2 it can be summarised that new process knowledge was identified and new manufacturing explicit, tacit and implicit knowledge was stored into MFIKM. In the next section the results for the second experiment are presented.

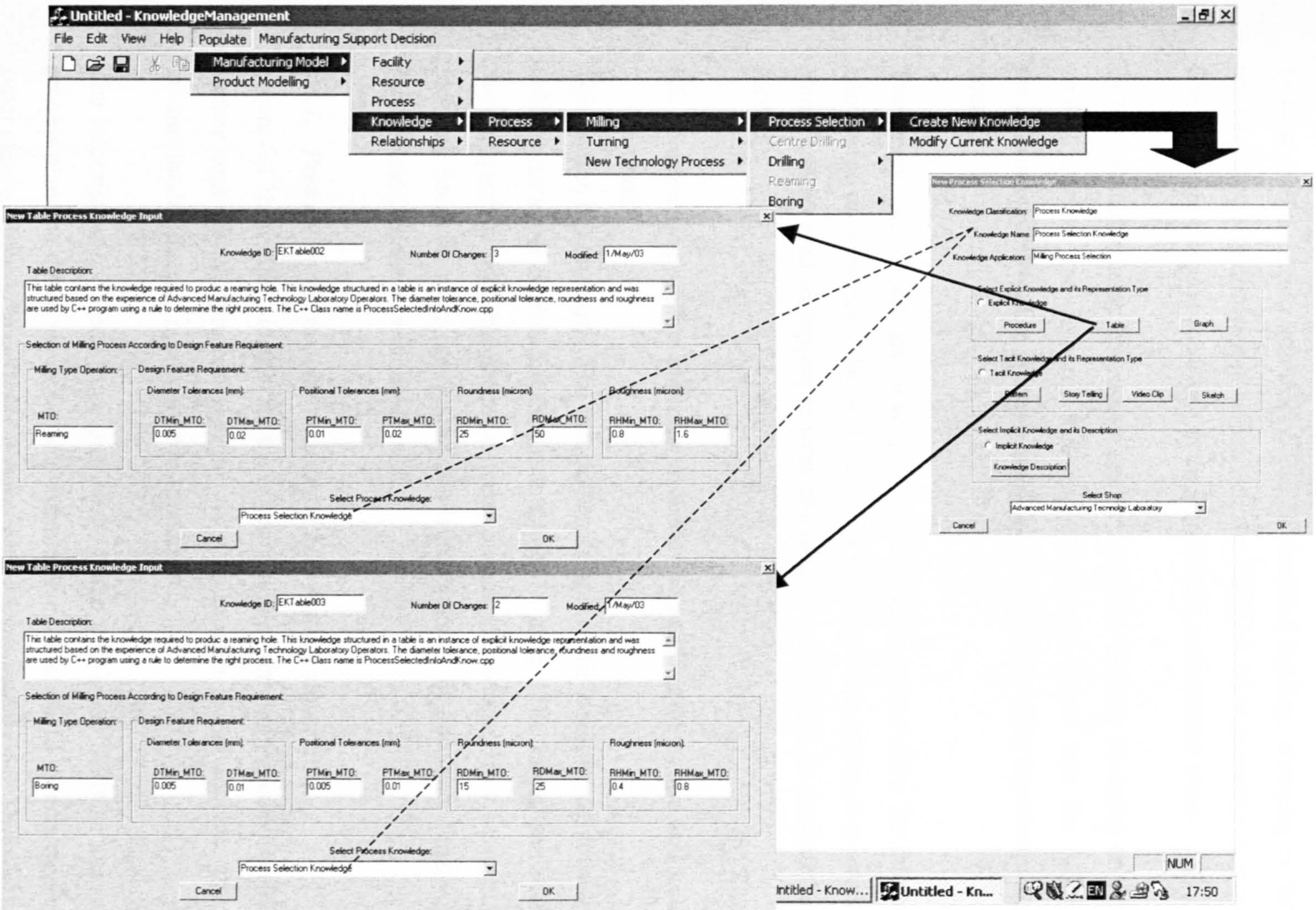


Figure 6-13 New process selection knowledge population (table) into MFIKM

6.4.3. The Evaluation of the Second experiment

As a result of the second experiment two important issues can be emphasised.

1) New manufacturing information can be modified (adding, changing or deleting) the current information instances stored into the MFIKM. New manufacturing information contexts were obtained according to the information maintenance done.

2) New manufacturing knowledge can be modified (adding, changing or deleting) the current process and resource knowledge instances stored into the MFIKM. New manufacturing knowledge contexts are obtained according to the knowledge maintenance done.

The second experiment has shown that the MFIKM structures allow the information and knowledge maintenance. The next step is to show how the information and knowledge stored can be used to support process planning decisions. This is presented in the next section.

6.5. Supporting process planning decisions using the information and knowledge stored.

This section has four parts. The first part explains how the experimental software uses the hole feature super class to link the product model concept. The second part shows how to Support process planning decisions using current knowledge. How to support process planning decisions using new knowledge is presented in the third part. Finally, the fourth part summarises the experiment results.

6.5.1. Product model population using a hole feature super class.

Figure 6-1 shows the structure for the experimental system implemented where the *hole-feature* super class represents the link with the product model concept. The complete product model diagram is presented in appendix C.

The information and knowledge previously stored within the MFIKM aims to support process planning decisions in the hole manufacture. Figure 6-14 depicts the *hole-feature* super class to store different holes features with the attribute shown. This was required to create the environment in which the information and knowledge can be used. Two hole instances with particular attributes are stored and used in this section to support process planning decisions.

HoleFeature
_holeType: char*
_maximumDiameter: double
_minimumDiameter: double
_depth: double
_holeAngle: double
_diameterTolerance: double
_positionalTolerance: double
_roundnes: double
_roughness: double

Figure 6-14 Product characteristics implementation super class

Figure 6-15 shows the dialog boxes in which the two *hole-feature* instances are entered. For example, a through end round hole with the particular dimensions in the respective dialog box is shown. In a similar manner, a tapered round hole instance is shown. The *hole-feature* instances were stored consistent with the attributes presented in Figure 6-14 and implemented respectively according to Figure 6-15.

6.5.2. Supporting process planning decisions using current information and knowledge.

This section presents how to support process planning decisions using current information and knowledge. The current information and knowledge is considered that was stored in section 6.3. Figure 6-16 represents the structure that contains the current information and knowledge that is used to support the round hole manufacture.

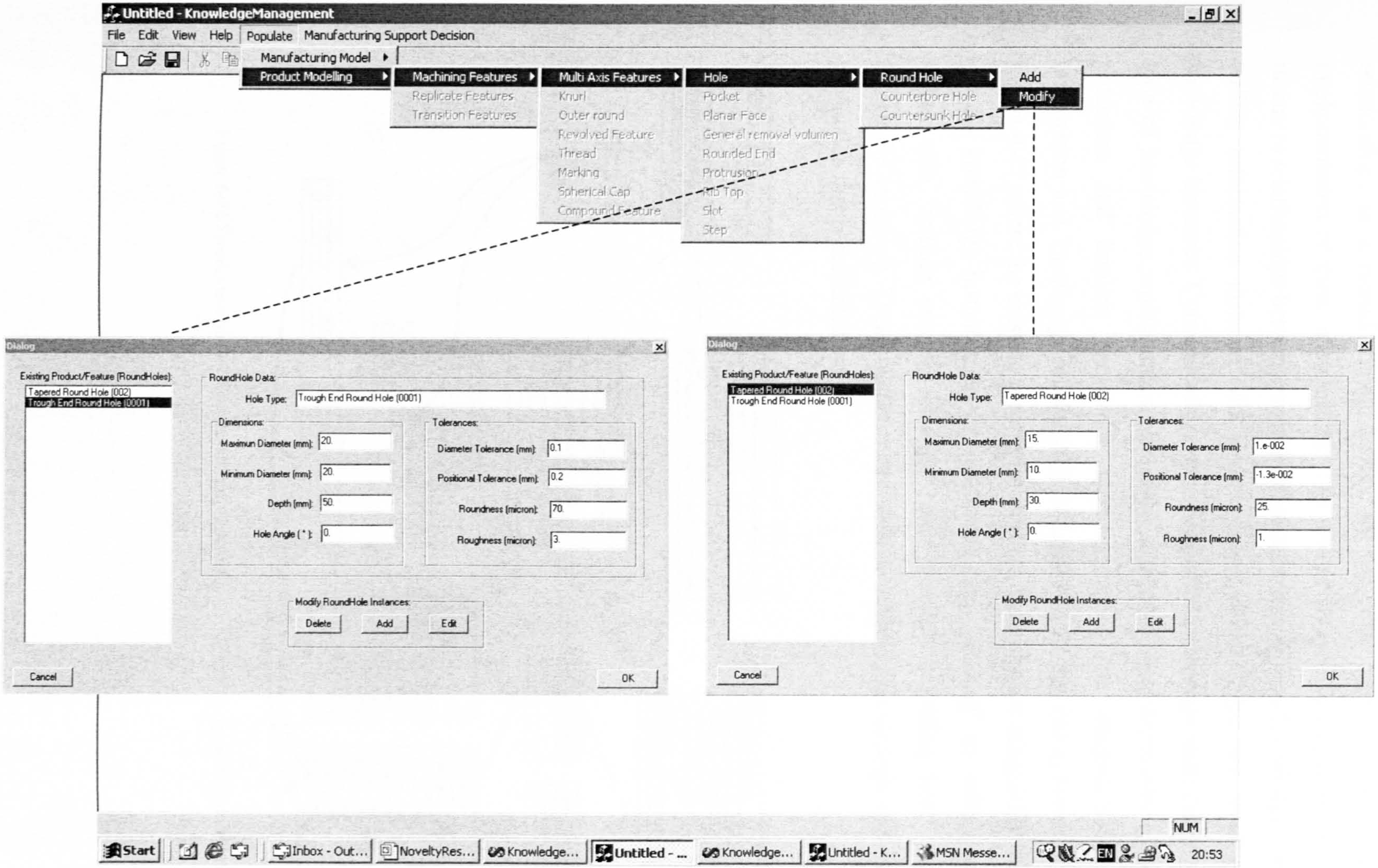


Figure 6-15 Hole feature class population used to represent the product model link

As previously commented in chapter 5, section 5.3, the information and knowledge relationships in a manufacturing facility are important and this section shows the implementation of these relationships. The arrows showed in Figure 6-16 depicts the instances relationships between process information and process knowledge. Particularly, *milling* information instance with *process-selection-knowledge* and *drilling-process-knowledge* instances. Consequently, *process-selection-knowledge* instances uses *table* as type of knowledge representation; similarly, *drilling-process-knowledge* instances use procedure and implicit knowledge representations. The implementation of the information and knowledge relationships is presented in the dialog boxes depicted in Figure 6-17 where the existing process information instances are assigned to the existing process knowledge instances. In this particular case, "drilling" as *milling* instance is linked with "milling process selection" and "produce a drilling hole" as *milling-knowledge* instances. These instances are used to support the through end round hole production that is presented next.

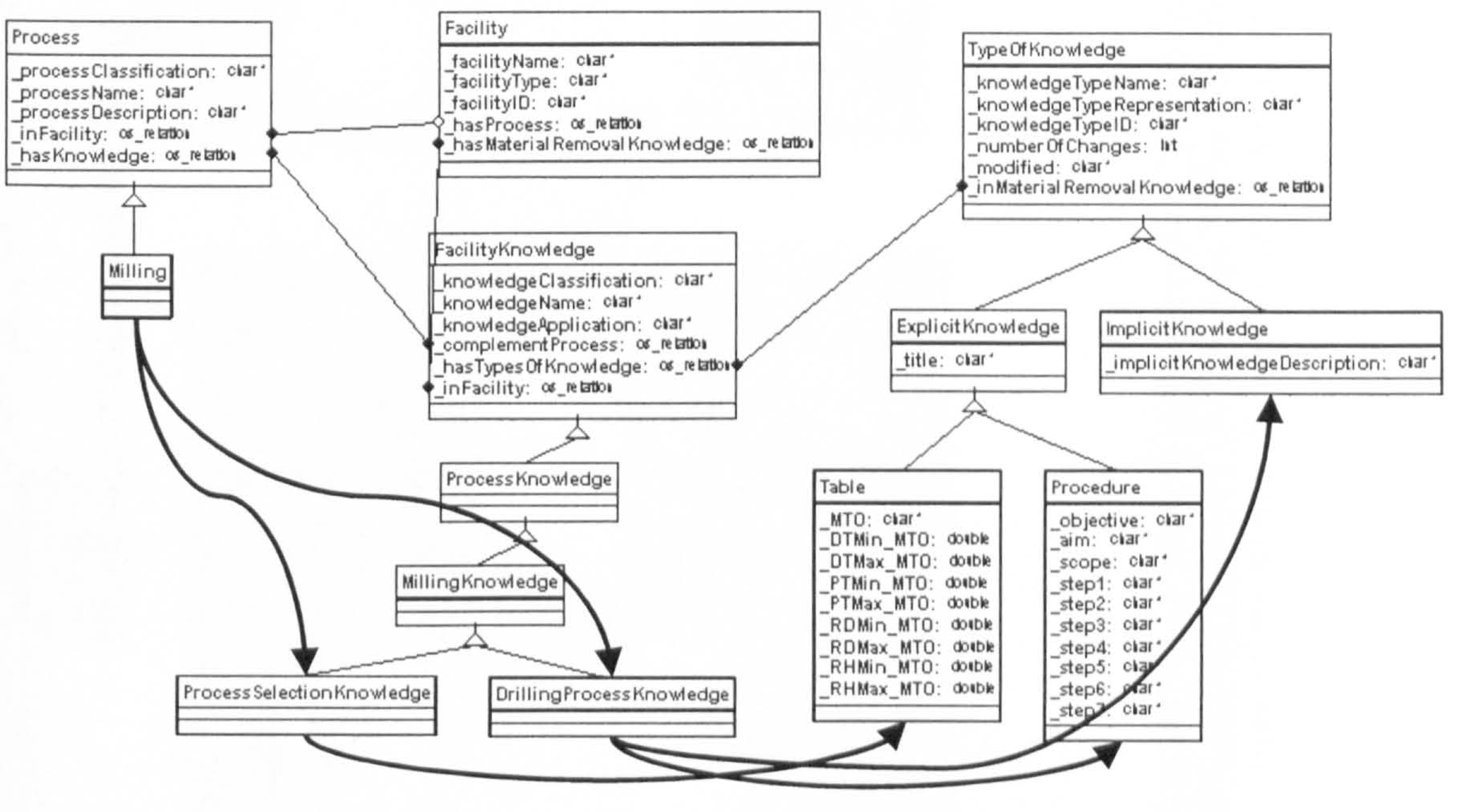


Figure 6-16 Process information and knowledge relationships to support the round hole production

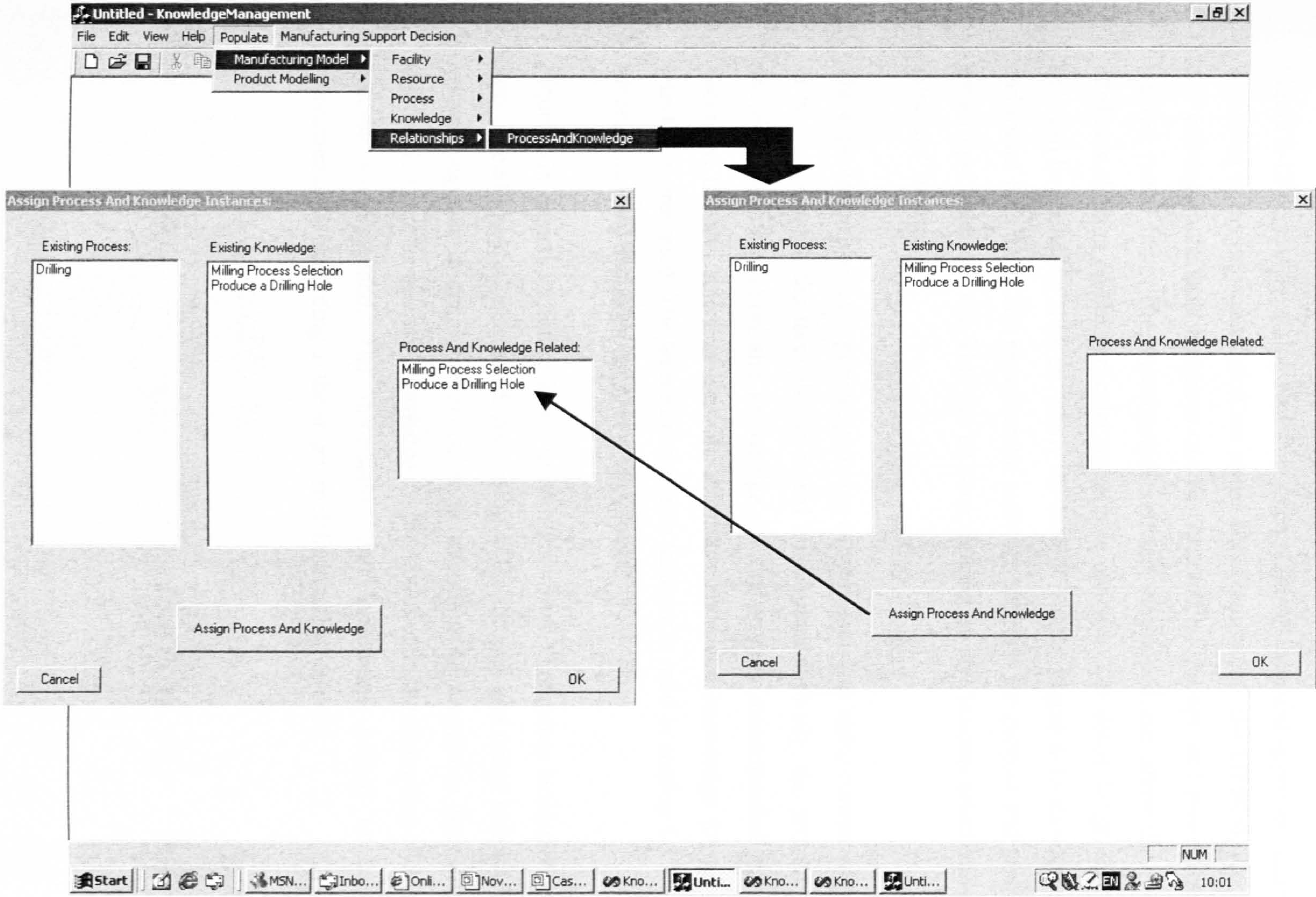


Figure 6-17 Process information and knowledge instances relationships to produce the round hole

At this stage the round hole instances were stored, the information and knowledge related to process was linked as well, then the next step is to show how a round hole selected applies the process information and knowledge stored.

Figure 6-18 depicts the dialog boxes in which is shown the existing product instances that according to the implementation are round hole features into the MFIKM. For example, two existing round hole instances can be observed, a) through end round hole, and b) tapered round hole. The experimental software developed can show the round hole attributes clicking on the particular round hole instance. The detail design for the round hole can be shown by click on "show me design" button. Figure 6-18 shows the through end round hole data. The experimental software supports the process and tool selection for a round hole selected. This can be done clicking on the "process selection" and "tool selection" buttons.

The explanation about the process planning support decisions using current knowledge is in two steps using the through end round hole instance. Firstly, the process selection showing the information and knowledge for the process recommended is presented. Secondly, the tool selection showing the information and knowledge for the resource selected is presented. The tapered round hole instance is used in section 6.5.3 to support process planning decisions using new knowledge.

Figure 6-19 depicts the dialog boxes in which is shown the process recommended for the through end round hole selected. According to the through end round hole attributes the system suggests a drilling process. It is important to emphasise that the process information and the process knowledge can be identified in the dialog box clicking on the process recommended. The information and knowledge related to the process recommended is according to the structure defined in Figure 6-16.

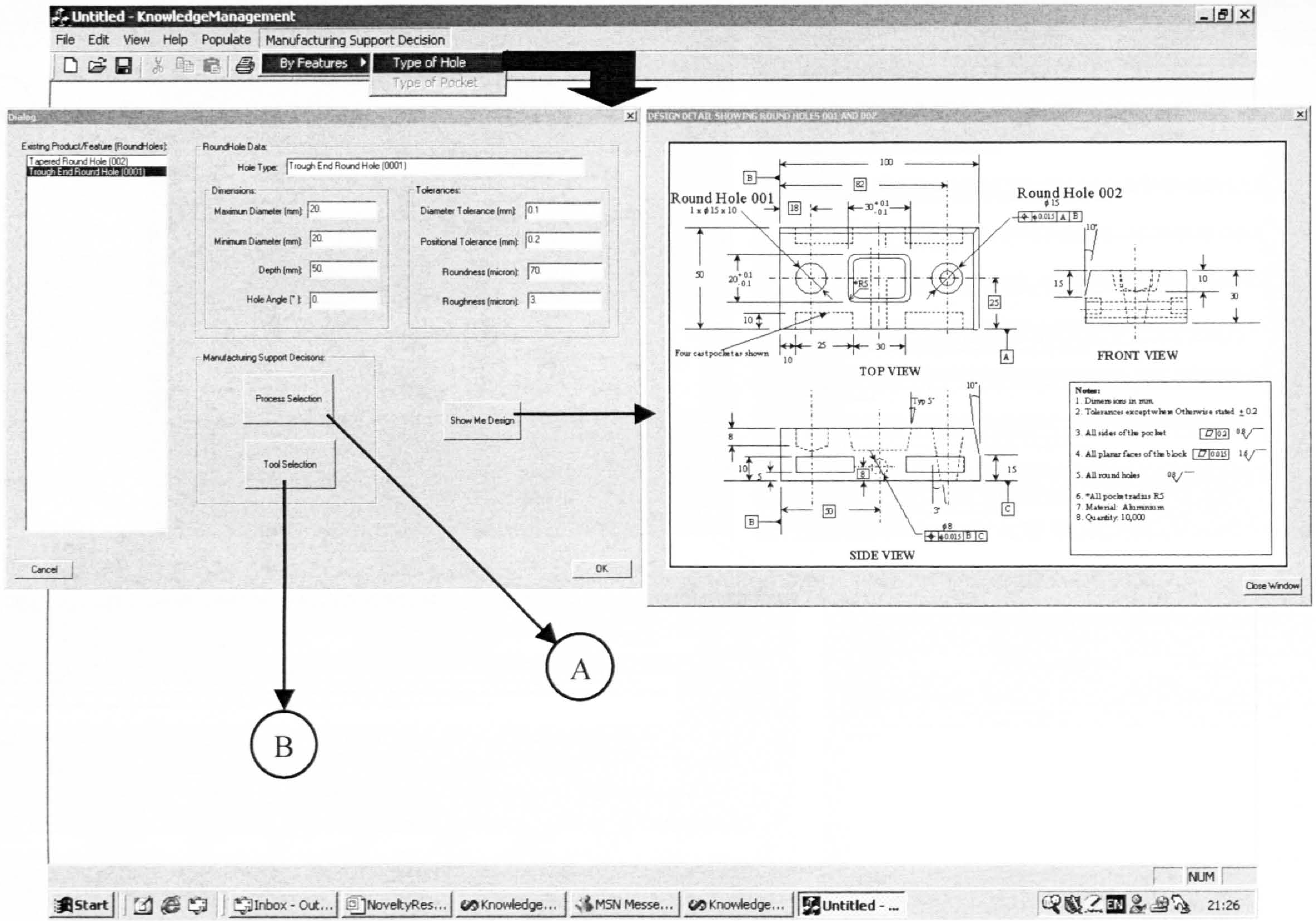


Figure 6-18 Round hole instance selection

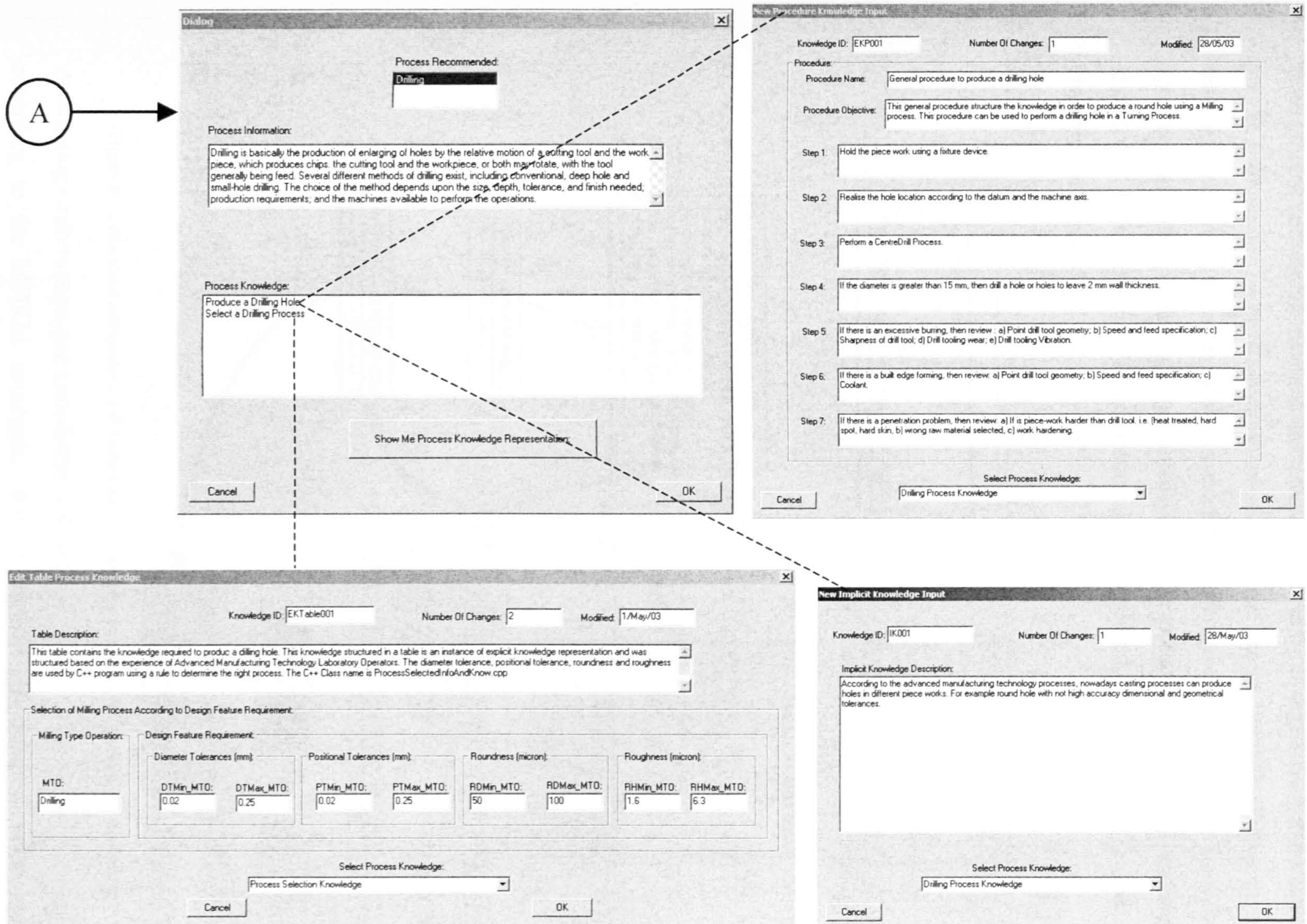


Figure 6-19 Round hole support decision using the information and knowledge stored

The software can provide a suitable machining process to produce a round hole. However, the software can provide the current information and knowledge related to the process recommended in addition. For example, in the process information definition and three process knowledge instances were shown. According to Figure 6-16 these instances are: an instance for *process-selection-knowledge* class named "select a drilling process" that use a table representation. Two instances for *drilling-process-knowledge* class named "produce a drilling hole" are presented; one is a procedure and other an implicit knowledge representation. These instances were stored in section 6.3.2 and now presented in Figure 6-19.

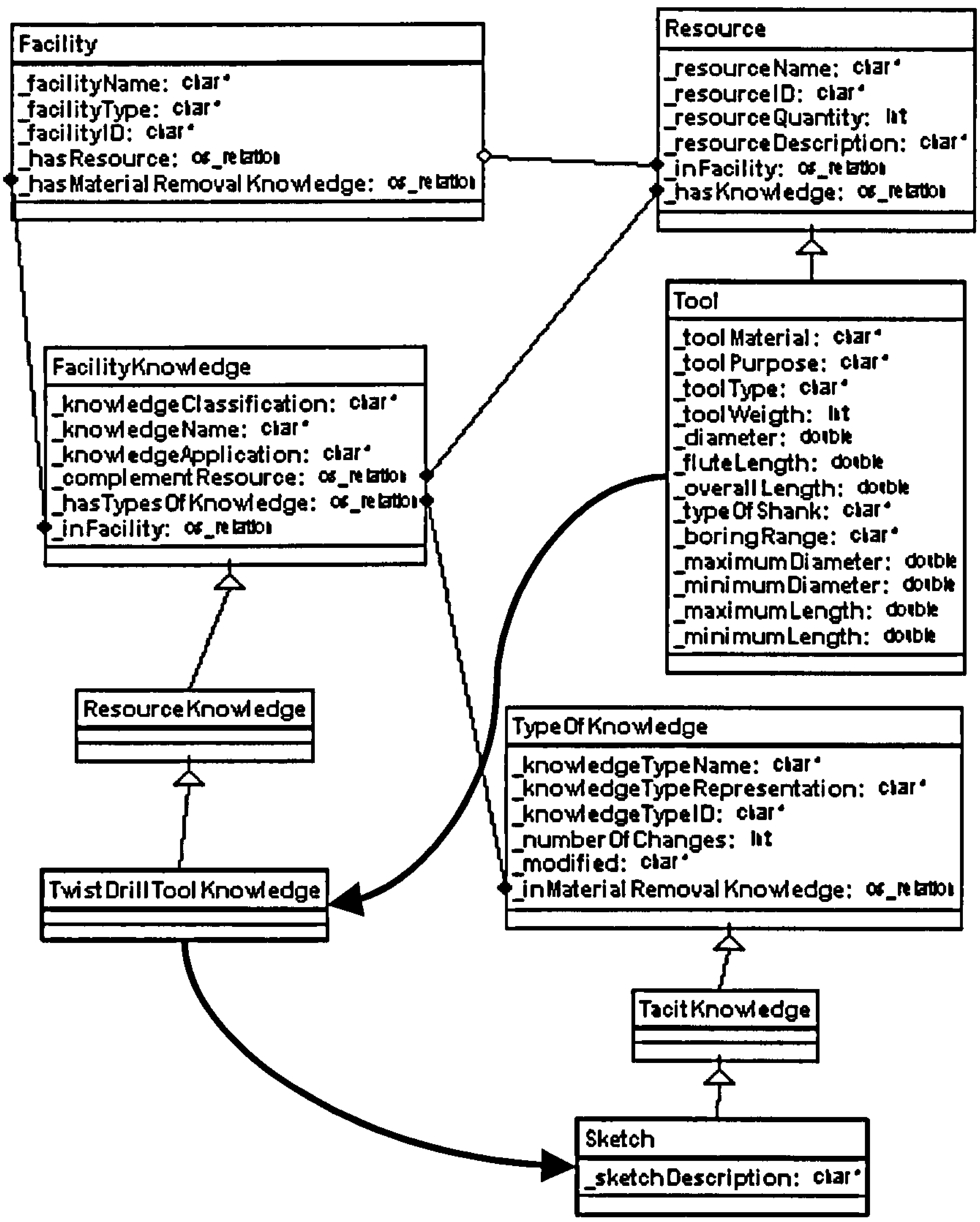


Figure 6-20 Resource information and knowledge relationships to support the round hole production

At this stage information and knowledge to support a process selection has been applied according to the MFIKM structures. How to support tool selection using current information and knowledge is presented next.

The resource information and knowledge relationships to support the round hole production are depicted in Figure 6-20. The arrows showed depict the instances relationships between resource information and resource knowledge. Particularly, *tool* information instances with *twist-drill-tool-knowledge* instances. Consequently, *twist-drill-tool-knowledge* instances uses *sketch* as type of knowledge representation. The assignation between the current *tool* information instances and the current *twist-drill-tool-knowledge* instances was done in a similar manner such as Figure 6-17 for processes information and knowledge instances.

Figure 6-21 depicts the dialog boxes in which the resource recommended for the through end round hole selected is shown. The system suggests the twist drill 002 according to the through end round hole attributes. The twist drill 002 is a particular resource stored previously in section 6.3.1. In addition, the resource information can be obtained by clicking on "show me tool information" button. In a similar manner, the resource knowledge can be obtained by clicking on "show me tool knowledge" button. Figure 6-21 presents the resource information and knowledge for the Twist drill 002 selected.

At the end of this section it can be observed that current information and knowledge related to processes and resources in a manufacturing facility can be used to support process planning decisions. The next section presents the support of process planning decisions using new knowledge.

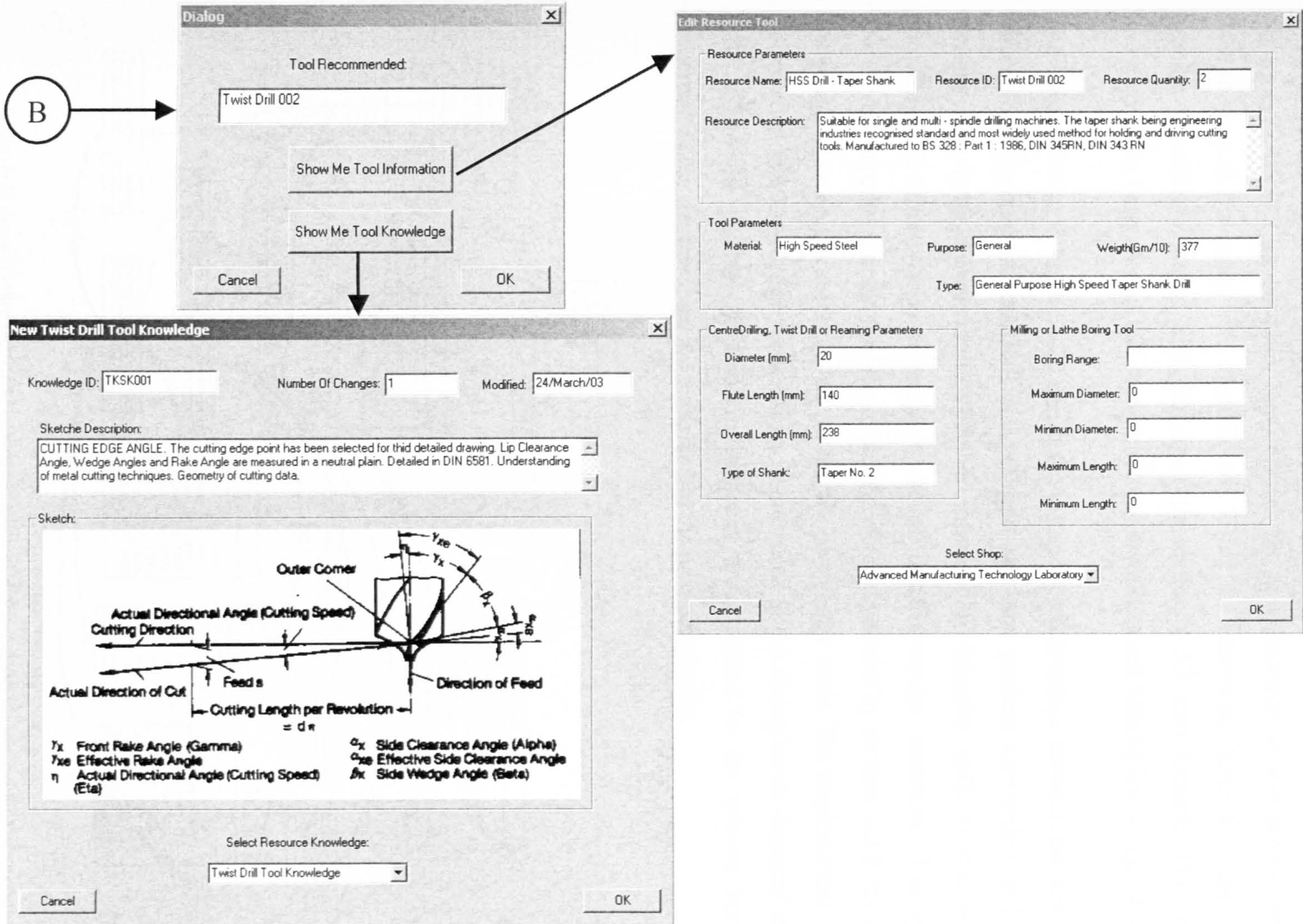


Figure 6-21 Resource information and knowledge to support the round hole production

6.5.3. Supporting process planning decisions using new information and knowledge.

This section presents how to support process planning decisions using new information and knowledge. The new information and knowledge is considered that was stored in section 6.4. Figure 6-22 depicts the structure that contains the new information and knowledge that is used to support the round hole manufacture. Using the arrows in Figure 6-22 the previous process knowledge stored and explained in section 6.3.2 can located. This previous knowledge has been used in this section to explain milling and turning knowledge sharing.

The arrows shown in Figure 6-22 depict the instances relationships between the new process information (turning information) and previous and new process knowledge (milling and turning knowledge). Particularly, *turning* information instance with *process-selection-knowledge*, *drilling-process-knowledge* and *turning-knowledge* instances. The types of knowledge representations for the instances were explained in section 6.3.2 for *milling-knowledge* class and in section 6.4.2 for *turning-knowledge* class. The implementation of the information and knowledge relationships is presented in the dialog boxes depicted in Figure 6-23 where the process information instances are assigned to the process knowledge instances. These relationships are explained in the next paragraphs.

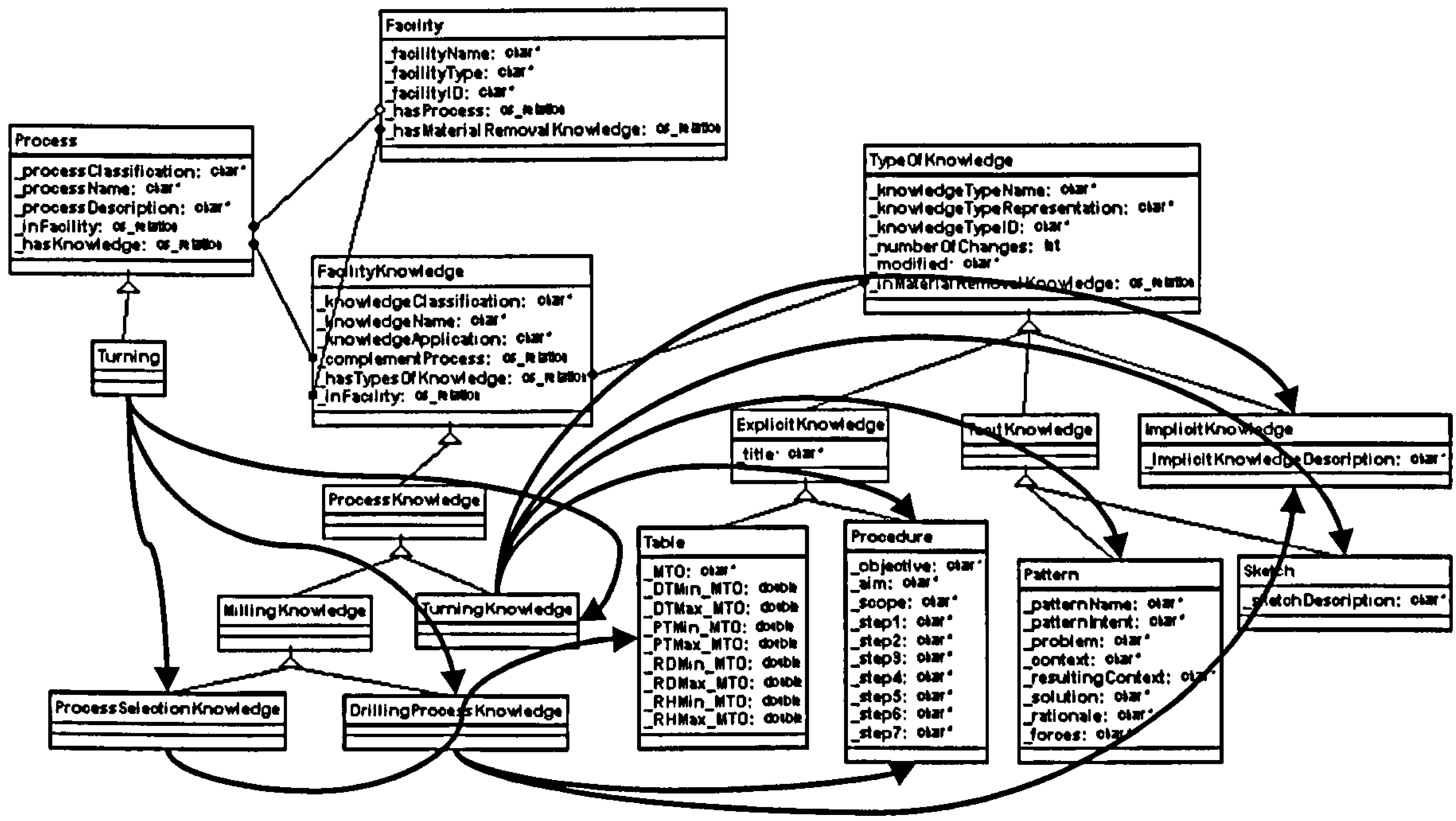


Figure 6-22 Process information and knowledge relationships to support the tapered hole production

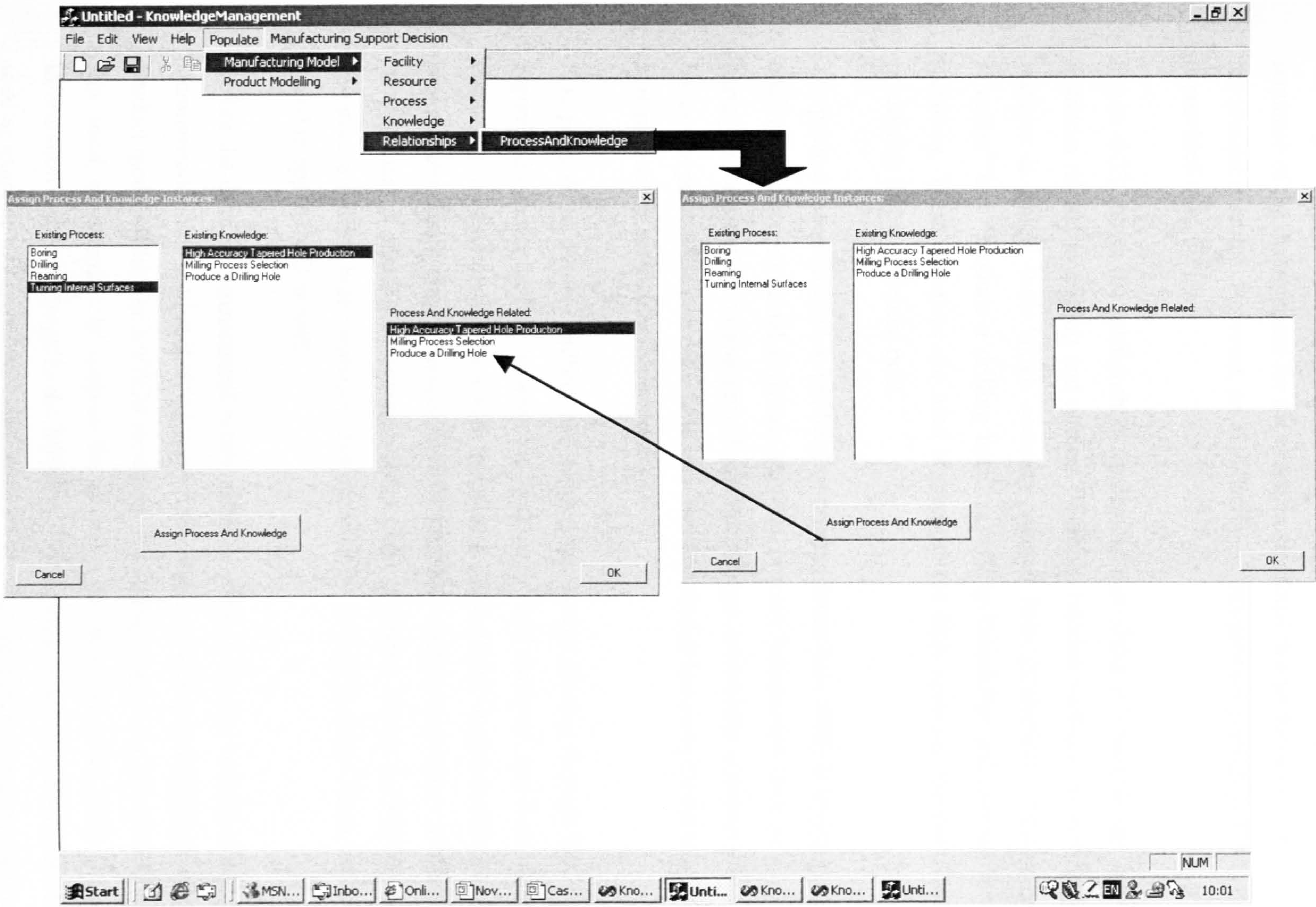


Figure 6-23 Process information and knowledge instances relationships to produce the tapered hole

Previous and new knowledge is used to support process planning decisions for the manufacture of a high accuracy tapered round hole. The sequence of dialog boxes showing the process planning support decision are attached in appendix D, because the sequence of the dialog boxes for the example explained in a previous section is similar to the present example. However, an explanation of this process planning support decision is provided next.

Figure 6-23 shows the relationships implementation about information and knowledge instances related to milling and turning. "Turning internal surfaces" as *turning* process instance is linked with "High accuracy tapered hole production", "milling process selection" and "produce a drilling hole" as *milling-knowledge* and *turning-knowledge* instances. These instances are used to support the high accuracy tapered round hole production that is presented next.

The process recommended to produce the tapered round hole (002) is boring process. In addition, the experimental software provides process information such as the current boring process definition and provides seven process knowledge instances. The dialog boxes that present the process information and knowledge instances for the tapered round hole production are attached in appendix D.

It is possible to observe milling and turning knowledge sharing through this example. Figure 6-23 shows the link between the "turning internal surfaces" that is an information instance related to *turning* class with "produce a drilling hole" instances that are *drilling-process-knowledge* class instances from *milling-knowledge* super class. In this manner *turning* class is sharing *milling-knowledge* class instances. Figure 6-19 shows the two "produce a drilling hole" instances that are used by turning process. These instances are added in appendix D as well.

Before the detailed experimental results analysis presented in the next section, it can be summarised in this section that two round hole instances were populated representing the product model within the MFIKM structure. The through end round hole (0001) instance was used as example to support the process and tool selection using the current information and knowledge in the MFIKM. The tapered round hole (002) instance was used as example to support the process selection using the previous and new information and knowledge in the MFIKM. It was shown that it is possible to share milling and turning knowledge to support the tapered round hole (002) process selection.

6.5.4. The Evaluation of the Third experiment

Using information and knowledge stored into the MFIKM, the experimental software created can support process planning decisions. The explanation in this section is divided in two main parts, the experimental results for: a) the current information and knowledge related to processes and resources to support process planning decisions to produce a through end round hole, and b) the previous and new process information and knowledge to support process planning decisions to produce a tapered round hole. In addition in this part the turning and milling knowledge sharing in mentioned.

a) Through end round hole 001 is selected to show the support of process and tool selection decisions using current information and knowledge.

To determine a suitable process to produce the round hole, the software uses the round hole design attributes and compares them with the process selection knowledge structured in a table knowledge representation. The process selection knowledge in a table knowledge representation is explicit manufacturing knowledge. By the identification of the suitable manufacturing process, the software provides information related to the process, for example the process definition. In addition, the system is capable of providing knowledge related with the process selected to support process planning decisions. In a similar manner this happens with a resource selected. In other words the software gives the support about general information related to a particular process or resource and the knowledge about them using the MFIKM structures.

b) Tapered round hole 002 is selected to show the support of process selection decisions using new information and knowledge. The milling and turning knowledge sharing is obtained in this example.

Previous and new process information and knowledge was used by the software to support how to bore a tapered round hole. In this experiment it was shown that as increasing complex the machining task is, the more useful it is to have different types of knowledge representations to support process planning decisions. The knowledge structure proposed can avoid the loss of valuable knowledge, because it is possible to store a rich variety of knowledge using different types of knowledge representations.

c) It was shown the milling and turning knowledge sharing combining the previous manufacturing process knowledge to produce a through end round hole and the new knowledge to produce a high accuracy tapered round hole.

6.6. Knowledge changes versus process planning decisions

This section has three parts. The first part presents the consequence of the knowledge instances change stored into the MFIKM. The second part discusses the consequence in the rule base programming change. The third part presents the fourth experiment results.

6.6.1. Knowledge instance change stored into the MFIKM

This section explains the consequence of the knowledge instances change stored into the MFIKM. The part of the experiment performed in this section uses the *process-selection-knowledge* class instances discussed and presented in section 6.5.3.

The previous *process-selection-knowledge* instances stored in the MFIKM consider CNC machines from the Advanced Manufacturing Technology Laboratory at Loughborough University (Shop 1, TW.0.01). The values obtained for the creation of these instances, mainly in the definition of the design features requirements such as: a) diameter tolerance, b) positional tolerance, c) roundness, and d) roughness considers the CNC machines accuracy to perform the drilling, reaming and boring processes.

The experiment performed in this section consists of the creation of the *process-selection-knowledge* instances considering the Engineering Application Laboratory at Loughborough University (Shop 2, TW.0.09), where mainly manual machines are included. More information about shop 1 and 2 can be found in appendix B.

The objective in this section is to define the process selection to produce the same round hole using the *process-selection-knowledge* instances from both shops. This experiment uses an additional instance stored into the hole-feature super class. The instance is a blind end round hole (003).

According to the similarity with the previous examples, the whole sequence of dialog boxes that presents the process selection for the blind end round hole (003) using shop 1 and 2 *process-selection-knowledge* instances is presented in appendix D. However, a brief description of the experiment is presented in the next paragraph.

Reaming process is the process recommended according to the blind end hole (003) attributes using manual machines. For the same blind end hole (003) instance but with the *process-selection-knowledge* instances for CNC machines, drilling process is the process recommended. The answer is logical because CNC machines can produce a machining part with higher accuracy than manual machines, then drilling process could be enough using CNC machines when reaming is required using manual machines.

6.6.2. Rule base programming change

There are different types of changes that can produce knowledge maintenance. As was presented in the previous section, sometimes it is required to modify only the knowledge value according to a table knowledge representation. This kind of knowledge change is only the modification of the particular value instance but the rule base doesn't change. However, there are kinds of changes where the rule base criteria need to change. For example, the current criteria that defines the types of machining process (drilling, reaming or boring) to produce a round hole is base on the comparison between the design features requirements such as: a) diameter tolerance, b) positional tolerance, c) roundness, and d) roughness and the values defined in the *process-selection-knowledge* instances. The software calculates a suitable machining process by programming. In the previous example only the values changed from shop 1 to shop 2. However, it could be a case where a new criteria is needed or a particular combination with different values is required. In this case it is required to change the rule base, defining a new rule in the program implemented for the software developed. Appendix D shows an example of the listing where the computational rule to select the milling process using the hole feature requirement is emphasised. If the rule criteria in the process selection change, this is the part of the code that needs to be changed.

6.6.3. The Evaluation of the Fourth Experiment

The process selection recommended to produce a blind end round hole is reaming process using the manual shop knowledge. However, a drilling process is recommended sufficient to produce the same hole changing the table knowledge according to a CNC shop. The software is able to provide different answer to produce the same round hole (blind end round hole 003) changing the process knowledge stored.

In some cases a criterion decision change can affect the knowledge-based rule, for example when additional criteria such as diameter tolerance, positional tolerance, roundness and roughness need to be added to define the process selection.

6.7. Summary

This chapter explains the development and implementation of the experimental system and demonstrates the result of the experiments.

The results show that the MFIKM structures explored in this work can capture information and knowledge related to process and resources in a manufacturing facility. The combination of the MFIKM and the knowledge maintenances method proposed support storage, maintenance, and sharing of manufacturing knowledge.

Information and knowledge update is possible because information and knowledge structures to add or replace new information and knowledge were created. The manufacturing information and knowledge structures explored in this work provide the capability to construct information and knowledge models which do not have to be restricted to particular industry areas. This research idea can be extended in other manufacturing domains.

CHAPTER 7

7. DISCUSSION, CONCLUSION AND FURTHER WORK

7.1. Introduction

This research has shown how a MFIKM can support storage, maintenance, and sharing of manufacturing knowledge. The information and knowledge to support process planning decision was used to explore how the MFIKM structures work. The novel approach to manufacturing knowledge maintenance composed by the maintenance method and the models structures has been investigated and an experimental system has been developed to verify the results.

This chapter discusses the contribution of the research reported in this thesis, and brings together a number of the major research issues, in order to allow a set of conclusions to be formulated and the recommendation for further work. Section 7.2 presents the discussion of the major issues explored in this thesis. Conclusions and further work are presented in sections 7.3 and 7.4, respectively.

7.2. Discussion

7.2.1. Understanding different type of knowledge and their representation

The understanding of different types of knowledge and their representation is important in manufacturing knowledge maintenance. Knowledge is a complex subject, however its comprehension in some areas is advancing using explicit, tacit and implicit knowledge definitions. The knowledge understanding is an important issue in the definition of the role of information and knowledge in knowledge maintenance. In a manufacturing facility there are a wide range of information and knowledge that needs to be structured and captured before being maintained. Manufacturing explicit knowledge can be captured using procedures, tables and graphs. In a similar manner, manufacturing tacit knowledge can be captured using patterns, story telling, video clips and sketches. In addition, manufacturing implicit knowledge can be captured by text. The information and knowledge in a manufacturing facility can be structured and captured using the different types of knowledge representations mentioned.

7.2.2. Definition of manufacturing model structures that enables the storing of different types of knowledge.

The discussion of the model structures is divided in four related parts. The first part is related to knowledge models. The second is related to information structures. Knowledge structures are discussed in the third part. The final part discusses information and knowledge relationships within the manufacturing model structures.

7.2.2.1 Knowledge models.

The MFIKM obtained in this approach differs from the traditional knowledge models defined in knowledge management approaches. The majority of the KM models are mainly focused on the understanding and the role of knowledge in KM (Nickols 2000), (Zheng et al. 2001), (Beckett 2001), (Koskinen 2003), (Carneiro 2000). The author of this thesis agrees with the need for an understanding of the role of knowledge in KM. The author of this thesis considers the KM models and approaches are useful in the creation of new knowledge models. For example, the creation of the MFIKM by the application of the current knowledge types definitions and its relationships. The MFIKM provides information and knowledge structures to store facility information and knowledge related processes and resources. However, the MFIKM is focused on the improvement of decision support systems.

7.2.2.2 Information structures.

This research has shown that information structures can store manufacturing facility information related to processes and resources. Three main super classes named: *facility, process and resource* are defined in the information structures. The information structures are based on Molina and Bell (Molina and Bell 1999) work. However, the new contributions in these structures are: 1) the creation of a process and resources classification based on ISO standards, and 2) the classes attributes definition allowing a clear distinction between facility information and facility knowledge. As a result three information structures were obtained: a) facility information structure, b) process information structure, and c) resource information structures. The information structures obtained provide an efficient repository for the manufacturing facility information.

7.2.2.3 Knowledge structures.

This research has shown that knowledge structures can store manufacturing facility knowledge related to processes and resources. Two main super classes named: *facility-knowledge* and *types-of-knowledge* are defined in the knowledge structures. Molina and

Bell (Molina and Bell 1999) defined a *strategy* super class to store possible manufacturing knowledge. However, they didn't explore knowledge structures in the manufacturing model to support storage and maintenance of manufacturing knowledge. *Facility-knowledge* super class categorises the processes and resources knowledge related to a manufacturing facility. *Types-of-knowledge* super class categorise the different types of knowledge that are used to express the processes and resource knowledge. As a result, three main knowledge structures were obtained: a) types of knowledge structure, b) process knowledge structure, and c) resource knowledge structure. The present research extends Molina and Bell's (Molina and Bell 1999) approach with a significant contribution to knowledge structures in order to update the manufacturing knowledge by applying a knowledge maintenance method.

7.2.2.4 Information and knowledge relationships within the manufacturing model structures

The relationships between information and knowledge within the MFIKM are an important issue to support decisions with updated knowledge. There are 7 relationships that make possible the information and knowledge representation in the MFIKM. These relationships are identified in Figure 7-1.

Four useful information relationships within the MFIKM have been identified in this work. Relationship 1 organises stations with a particular cell and relationship 2 organises cells with a particular station. These two relationships can manage important facility information depending on the attributes defined for each facility. This type of relationship can be extended for additional facilities such as: factory and enterprise level. Relationship 3 organises the facility instances with process information. This relationship enables the connection between the whole process information with a particular facility. This research has shown the relationship between milling and turning information with facility shops, however it can be extended for other material removal processes such as: grinding, EDM and even for material addition processes such as welding, etc. Relationship 4 organises the facility instances with the resource information. This relationship enables the link between the whole resource information with a particular facility. The current implementation includes the shop information relationship with tools and machinery resources, however it can be extended to other kind of resources such as: stock material, etc. These four relationships can allow the facility information capture that provides the facility overview. The four relationships provide significant information contexts with useful manufacturing meaning.

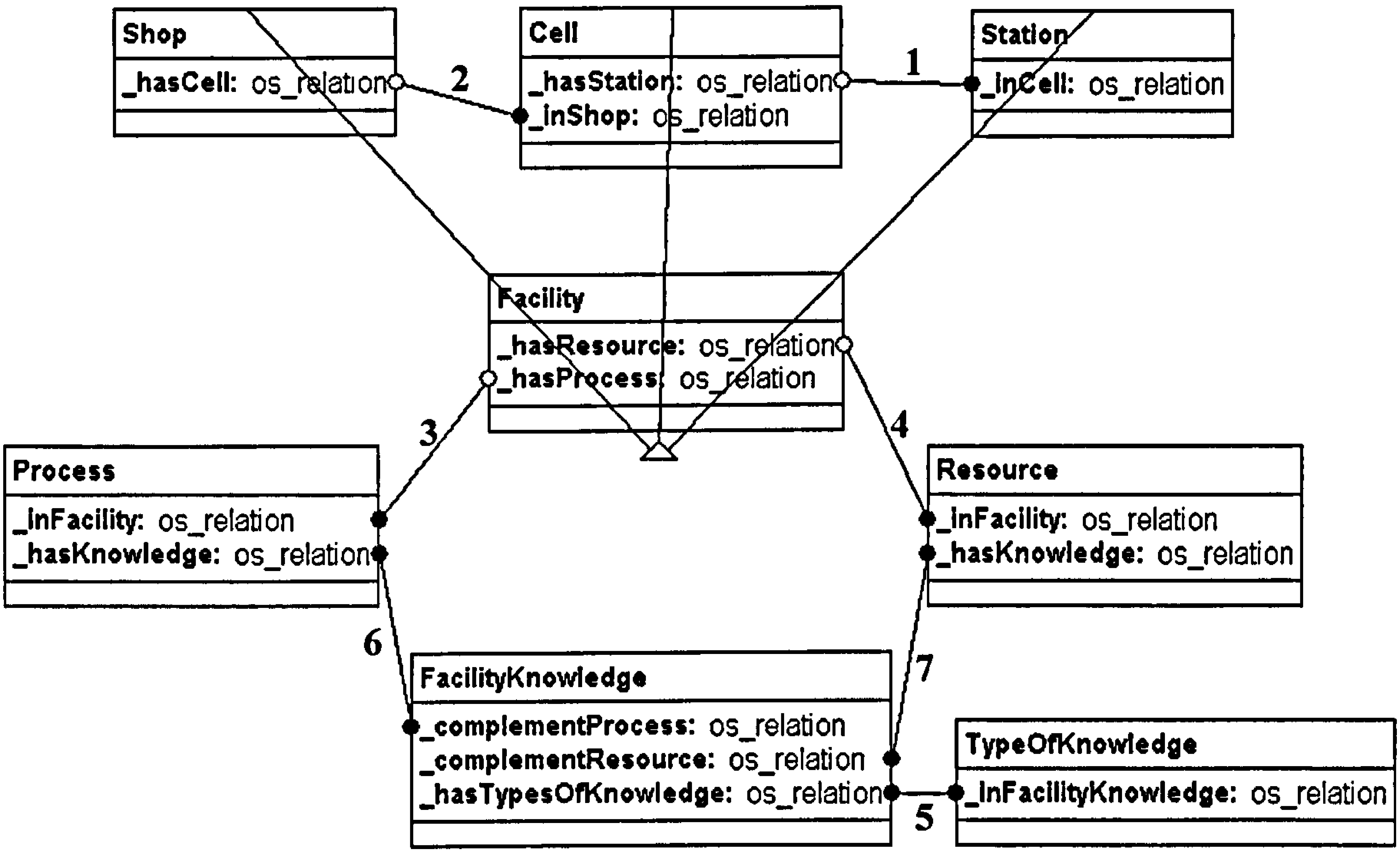


Figure 7-1 MFIKM relationships

Relationship 5 allows useful manufacturing knowledge representation. Using this relationship two significant functionalities have been identified in this work. The first is the process knowledge representations using explicit, tacit and implicit knowledge types. In a similar manner, the second is the resource knowledge representations using explicit, tacit and implicit knowledge types. Using this knowledge structure it is possible to provide process and resource knowledge. The current process knowledge implemented is related to milling and turning. However, this implementation can be extended to the whole process knowledge in the manufacturing facility, for example, process knowledge related to grinding, EDM, assembly, etc. The current resource knowledge implemented is related to tools. However, this implementation can be extended to the whole resource knowledge in the manufacturing facility, for example, resource knowledge related to machinery, stock material, etc. The current knowledge types categorisation implemented includes explicit, tacit and implicit knowledge representations, however, these knowledge types and their representations can be expanded. This knowledge relationship provides knowledge availability related to processes and resources in a manufacturing facility combining the facility knowledge and types of knowledge representation. Knowledge contexts are the different facility knowledge organised by the types of knowledge. The knowledge contexts related to processes and resources were used in this research to support process planning decisions, however they can be used for other manufacturing decisions such as assembly.

Relationship 6 enables the combination of information and knowledge related to manufacturing processes. Two important implementations using relationship 6 have been identified in this work. The first provides useful information related to a process selected and what is known related to that particular process, according to the experimental software created. A typical KBS provides an answer for a particular question (Chung et al. 2003). For example, drilling, reaming or boring as process selection answer to produce a round hole in a typical KBS can be provided. However, the experimental software created provides valuable process information and knowledge stored into the MFIKM using the relationship 6. The information and knowledge sharing between manufacturing processes is an additional important implementation using this relationship. For example, the whole or a particular piece of milling process knowledge can be shared for the turning process and vice versa. These two implementations for the relationship mentioned were shown in chapter 6, section 6.5. The combination of information and knowledge related to manufacturing processes can be further expanded to other manufacturing processes in the MFIKM, assembly for example.

In a similar manner, the use of the relationship 7 allows useful combination of information and knowledge related to manufacturing resources. Two important performances using relationship 7 have been identified in this work. The first provides useful information related to a resource selected and what is known related to that particular resource. The experimental software created provides valuable resource information and knowledge stored into the MFIKM using the relationship 7. The implementation for this relationship was shown in chapter 6, section 6.5. Additional important performance using this relationship is the information and knowledge sharing between manufacturing resources. For example, the whole or a particular piece of twist drill knowledge can be shared for the reamer resource and vice versa. The information and knowledge structure relationships of resources can be further expanded to other manufacturing resources in the MFIKM, assembly resources for example. Although this research has explored the application of MFIKM to support storage, maintenance and sharing of manufacturing knowledge, these four relationships will be significant for other information models such as the product model.

7.2.3. The definition of methods to support the manufacturing knowledge maintenance

This work has explored the concept of the knowledge maintenance life cycle applied to the MFIKM. The knowledge maintenance life cycle has been created and implemented to act as knowledge maintenance method. This knowledge maintenance method is an important part of the research presented in this thesis and was presented in chapter 3 and implemented in chapter 6. Information, rule based criteria and knowledge has been identified as main areas to bring up to date in the knowledge maintenance life cycle. However, the concept can be extended to a combination these areas.

The knowledge maintenance life cycle included significant knowledge transformations. For example: explicit, tacit, and implicit knowledge transformations. These transformations were made following the different types of knowledge concepts. However, fuzzy aspect could be considered within the cycle to support these transformations.

The knowledge maintenance method implemented applied a logical sequence to guide the information, rule based criteria and knowledge maintenance. Following the maintenance method applying to the information and knowledge within the MFIKM obtain the knowledge maintenance. However, the possibility to support the knowledge maintenance automatically by AI tools can be explored. For example, the full integration of the KM method and the MFIKM structures could enable the knowledge update automatically. Finding this could be possible that the information and knowledge captured within the MFIKM can be updated such as the learning process.

7.2.4. Tools and techniques that support information and knowledge modelling

The combined integrated tools applied in this research proved to be useful in the information and knowledge modelling from the capture of the process planning information and knowledge through the creation of the classes and objects required in and object-oriented database.

UML is robust in modelling information and knowledge structures that is based on the information classes (object groups). UML class diagrams were used to design and analyse the information and knowledge structures obtained. UML proved to be a valuable tool to show in detail the classes an their attributes necessary for providing the MFIKM with the capabilities of being a source and repository of information and knowledge related to a manufacturing facility. The UML diagrams of the information and knowledge structures are presented in chapter 4 and appendix C.

7.2.5. The MFIKM implementation

The experimental system designed and implemented has been shown to be adequate for exploring the research ideas discussed in this thesis. However, it was identified that in order to test and validate the research concept, a variety of manufacturing challenges were required. They are discussed in the next paragraphs.

The design and definition of the information and knowledge structures required an in depth analysis of information and knowledge modelling. Appendix C presents the whole system developed that was explored to obtain the final structures implemented. However, the application of the UML tool has provided effective support for the design and representation of the experimental software developed.

The information and knowledge in a manufacturing facility needs to be captured and organised before stored into the MFIKM. Examples of the information and knowledge are presented in chapter 4. However, it has demonstrated in chapter 6 how the MFIKM can store, maintain updated and share the information and knowledge related to processes and resources in a manufacturing facility using the support of process planning decisions to validate the MFIKM structures.

ObjectStore© database was used to store the information and knowledge in the implementation of the MFIKM. The functionality of the software application has been realised by using Microsoft Visual C++©. As a result, a rudimentary experimental system has been implemented to highlight the knowledge contribution. The combinations of ObjectStore database and Microsoft Visual C++© have provided good support in order to test and validate knowledge maintenance ideas. However, some limitations were found in order to represent the variety of types of knowledge representations. For example, the storage and management of tacit knowledge representation such as video clips and sketches. It was found that new software applications could provide better functionality storing and managing video clips and PDF files.

7.2.6. Experiments result Analysis.

Manufacturing information and knowledge related to processes and resources to support process planning decisions was used to explore the MFIKM structures. The information and knowledge by two machining shops at Loughborough University to support process planning decisions for the holes manufacture has explored the MFIKM structures. However, there is a need to investigate how applicable is the concept of the MFIKM structures to support other type of decisions in the manufacturing facility. Also, there is a need to investigate how a MFIKM could be used by others decision support systems based on knowledge. The result of the experiments could have been interrogated based on the types of manufacturing knowledge stored and used to support decisions with knowledge updated.

7.3. Conclusions

I.) It has been shown that the structures defined for the MFIKM can serve as a source and repository for manufacturing information and knowledge related to facilities, processes and resources to support process planning decisions with information and knowledge.

II.) It has been shown, in chapter 6, section 6.4 that a MFIKM, operating in a knowledge support environment, can support knowledge maintenance. The novel approach to manufacturing knowledge maintenance has been defined in terms of a knowledge maintenance method, the MFIKM structures, and relationships within the manufacturing model structures that have been discussed in chapters 3,4, and 5.

III.) It has been shown that procedures, tables and graphs as explicit knowledge representations; patterns, sketches, story telling and video clips as tacit knowledge representations and implicit knowledge captured by text; have been proven to provide wide range of manufacturing knowledge capture. As demonstrated in chapter 4.

IV.) It has been shown, using information and knowledge to produce a round hole as a kind of manufacturing knowledge (chapter 4), that an effective MFIKM structure must represent not only information related to processes and resources, but also the knowledge associated with the processes and resources. The knowledge, capture through the model structures and its relationships, ensure knowledge maintenance, as demonstrated in chapter 6.

V.) The definition of the information structures interaction provides an effective means of representing a wide range of manufacturing information related to facilities, processes and resources. This structure discussed in chapter 4, section 4.3, allows conditions to be captured quickly and efficiently, and enables multiple relationships providing useful information contexts. As demonstrated in chapter 6, section 6.5.2.

VI.) It has been shown that the definition of the knowledge structures interaction provides an effective means of representing a wide range of manufacturing knowledge related to processes and resources. This structure discussed in chapter 4, section 4.4, allows complex conditions to be captured quickly and efficiently, and enables multiple interactions providing useful knowledge contexts. As demonstrated in chapter 6, section 6.5.3.

VII.) It has been shown that information and knowledge relationship provides an effective information and knowledge sharing environment. This enables the retrieval of processes and resources information and a flexible means of knowledge sharing availability. This has been demonstrated through the experiments in chapter 6, section 6.5.

VIII.) It has been shown that the KM models and approaches have been useful in the definition of the knowledge maintenance life cycle. The knowledge maintenance life cycle provides an effective knowledge maintenance method. This has been demonstrated through the experiments in chapter 6.

IX.) The use of the tools and techniques for information and knowledge modelling proved to be effective support in the design of the experimental system. UML provides a consistent notation for the creation and representation of the classes and detailed attributes for the design and development of the MFIKM structures.

X.) Experimental software has been implemented using the object-oriented database ObjectStore© and the Visual C++ programming environment. This system has explored using real cases from the two Loughborough machining laboratories to successfully demonstrate the feasibility of the MFIKM concept to support knowledge maintenance.

7.4. Recommendations for Further Work

I.) This research has defined information and knowledge structures to represent a MFIKM and has identified how this model can support storage, maintenance and sharing of manufacturing knowledge. The implementation and validation of this model by the use of information and knowledge updated to support process planning decisions has also been demonstrated. However, there is a need to investigate the application of the knowledge maintenance using the MFIKM structures at other manufacturing levels, i.e. factory and enterprise level.

II.) This research has explored knowledge structures using explicit, tacit and implicit knowledge concepts to store manufacturing knowledge. However there is a need to explore additional knowledge types. There is also a need to investigate additional knowledge representations emphasising the differences between knowledge types.

III.) There is a particular need to explore additional examples to emphasise the difference between tacit and implicit knowledge type.

IV.) This research has explored how to maintain knowledge using different types of knowledge. However, there is a need to explore the manufacturing meaning that can be obtained with information relationships versus the knowledge captured within the MFIKM. This to emphasise differences between information and knowledge representations.

V.) It has been shown that the MFIKM can support the association between information and knowledge, i.e. information and knowledge related to processes. However, no investigation has been completed into how to associate facility knowledge, i.e. relationships between process knowledge and resource knowledge. There is a need for further work in exploring how knowledge about processes can provide additional support for resources.

VI.) In this research, the modelling of manufacturing knowledge has been realised using different types of knowledge representation. In this stage the main attention was in providing a wide range on knowledge contexts. However, there is a need to investigate the optimisation of the knowledge stored.

VII.) This research has explored the knowledge maintenance based on different conceptual knowledge transformations. However, fuzzy aspect could be considered within the cycle to support these transformations.

VIII.) In this research, the MFIKM was implemented using an experimental software application to show knowledge maintenance ideas. However, there is a need to investigate the combination of this model's structures and the knowledge maintenance method using AI technology. For example, in the application of the information and knowledge automatically updated.

IX.) This research has explored the information and knowledge modelling using the same model structure. However, there is a need to explore the MFIKM using information models and knowledge models separately. This in order to explore advantages and disadvantages of information and knowledge relationship is a same model and in separated models.

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APPENDIX A. Tools and Methods Used in the Research

A-1. UNIFIED MODELING LANGUAGE

A-1.1. Rational Rose 2000

Rational was an early leader in the adoption of the Unified Modeling Language, was first to deliver an integrated lifecycle development solution, and has taken change management to a new level through Unified Change Management. UML is an accepted industry standard originally created by Rational and today managed by the Object Management Group (OMG). The UML unifies developers around the world by providing a single language for application, data, business, Web, XML, and test modelling (Rational 2003).

A-1.2. Unified Modeling Language (UML)

UML is a notation that resulted from the unification of OMT (Object Modeling Technique) (Rumbaugh 1991), Booch (Booch 1994), and OOSE (Object-Oriented Software Engineering) (Jacobson 1992). UML has been designed for a broad range of applications. Hence, it provides construct for a broad range of systems and activities (e.g., real-time systems, distributed systems, analysis, system design, and deployment) (Bruegge 2000).

UML is a standard language for writing software blueprints. The UML may be used to visualise, specify, construct and document the artifacts of a software intensive system. Visualising, specifying, constructing and documenting object-oriented systems is exactly the purpose of the Unified Modeling Language (Booch et al. 1999).

The UML is appropriate for modeling systems ranging from enterprise information systems to distributed Web-based applications and even to hard real times embedded systems. It is a very expressive language, addressing all the views to develop and then deploy such systems (Booch et al. 1999).

The UML is the successor to the wave of object-oriented analysis and design (OOA&D) methods that appeared in the late '80s and early '90s. It most directly unifies the methods of Booch, Rumbaugh (OMT), and Jacobson, but its reach is wider than that. The UML went through a standardisation process with the OMG (Object Management Group) and is now on OMG standard (Flower and Scott 2000).

The UML is called a modelling language, not a method. Most methods consist, at least in principle, of both a modeling language and a process. The modeling language is the (mainly graphical) notation that methods use to express design. The process is their advice on what steps to take in doing a design. The modeling language is the most important part of the method. It is certainly the key part for communication. If you want to discuss your design with someone, it is the modeling language that both of you need to understand not the process you used to get that design (Flower and Scott 2000).

A-2. OBJECTSTORE

A-2.1. ObjectStore Designer

ObjectStore Database Designer is a feature of ObjectStore that helps you create ObjectStore databases quickly and easily. Its graphical user interface (GUI) helps you create and maintain the elements of an ObjectStore database — its classes, data members, relationships, methods, and indexes (ObjectStore 2003).

A class is the first element you create using the Database Designer. Once a class is defined, you can add data members and methods, or you can define other classes — you do not have to define data members at the time you define the class. Classes are always created as persistent objects. A persistent object is one that is stored in a database. Compare to a transient object, which is stored on the ordinary heap.

The default class name is CClass_n, where n is a unique number. You can change the default value, change the name at the time you create the class, or edit the name later.

The database diagram provides a higher-level view of your database design. The database diagram shows you at a glance which classes are related and how. You can choose from two styles of standard modeling notation — OMT (object modeling technique), shown in the figure B.5, or UML (uniform modeling language).

After create the database diagram in ObjectStore designer is possible to obtain automatically the C++ program.

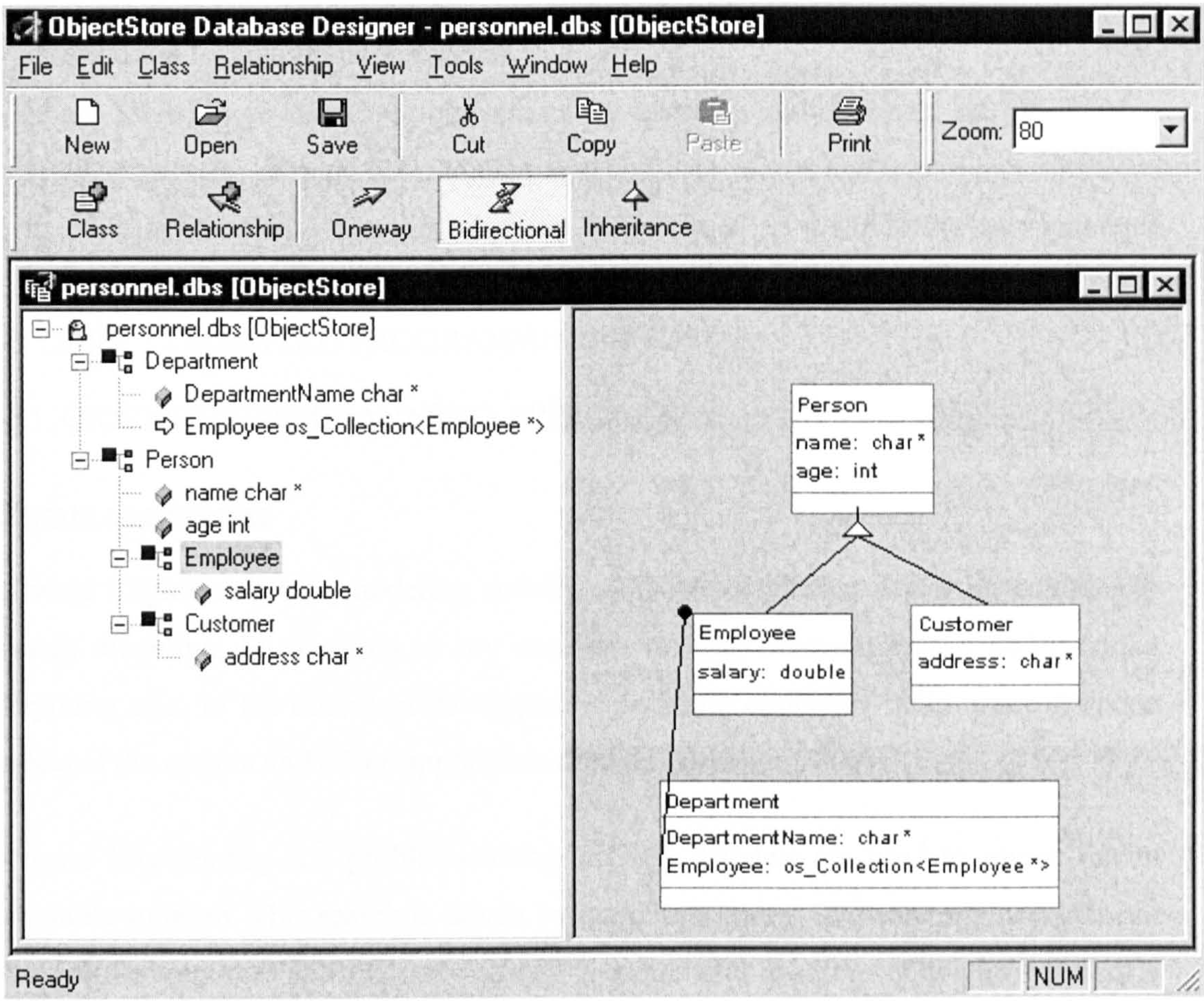


Figure A- 1 Database designer (ObjectStore 2003).

A-2.2. ObjectStore Inspector

ObjectStore Inspector is a graphical tool that lets you browse, edit, query, and report on the data in an ObjectStore database (ObjectStore 2003). Using Inspector, you can:

- Analyse and document the logical information represented by ObjectStore database schemas. Inspector's data views let you filter and order ObjectStore collections, and you can use database views to create custom schema diagrams. You can navigate instance relationships, and save the resulting navigation path for future use.
- Create, read, update, and delete ObjectStore application data in test and production environments — you can work with ObjectStore data directly from Inspector using manual editing tools and user-defined methods.
- Analyse the physical characteristics of ObjectStore databases at the segment, page, and instance level. The Physical Database Layout window provides detailed space and free space information and enables you to look up a particular instance based on

its address or segment offset. You can also review layout, segment, and binary dump information for individual instances.

- Share ObjectStore database information by creating reports based on ObjectStore application data, printing schema diagrams and data views, and exporting collections to other applications. You can also use Inspector as an OLE server in documents from OLE container applications.

A-3. OBJECT ORIENTED PROGRAMMING WITH C++

A-3.1. ORIENTED PROGRAMMING APPROACH

Software engineering

Software Engineering is a modeling activity. Software engineers deal with complexity through modeling, by focusing at any one time on only relevant details and ignoring everything else. In the course of development, software engineers build many different models of the system and of the application domain (Bruegge 2000).

Software Engineering is a problem-solving activity. Models are used to search for an acceptable solution. This search is driven by experimentation. Software engineers do not have infinite resources and are constrained by budget and deadlines. Given the lack of a fundamental theory, they often have to rely empirical methods to evaluate the benefits of different alternatives (Bruegge 2000).

Software engineering is a knowledge acquisition activity. In modeling the applications and solution domain, software engineers collect data, organise it into information, and formalise it into knowledge. Knowledge acquisition is non-linear, as a single piece of data can invalidate complete models (Bruegge 2000).

Software engineering is a rationale-driven activity. When acquiring knowledge and making decision about the system or its applications domain, software engineers also need to capture the context in which decisions were made and the rationale behind these decisions. Rationale information represented as a set of issue models, enables software engineers to understand the implication of a proposed chance when revisiting a decision (Bruegge 2000).

Object-oriented language today

A number of object-oriented programming languages are available today, with some significant differences between their capabilities and the extent to which they adhere to the object-oriented paradigm. Figure B.1 shows the characteristics of some widely used object-oriented languages (Bennett et al. 2002).

Feature	Smalltalk	C++	Eiffel	Java
Strong Typing	✓	Optional	✓	✓
Static/dynamic typing (S/D)	D	S	S	S+D
Garbage collection	✓	×	✓	✓
Multiple inheritance	×	✓	✓	×
Pure objects	✓	×	✓	×
Dynamic loading	✓	×	×	✓
Standardise class libraries	✓	×	✓	✓
Correctness constructs	×	×	✓	×

Figure A- 2 Characteristics in object-oriented languages (Bennett et al. 2002).

Why use C++?

Until comparatively recently, software engineering involved two distinct group of individuals. In the first group were the technical programmers, in their 'Real programmers don't eat Pascal' T-shirts, writing FORTRAN or C programs for scientific and engineering applications. In the second group were the business and commercial programmers wearing suits: their work centred on the database, typically storing financial and business information, and their programs were written in COBOL. By and large, the technical and business programming communities could be said to have a little in common (Pont 1996).

Now, the situation is different. In part driven by a 'downsizing' move from mainframes to networked microcomputers, and partly by and increasing demand from users for interactive, user-friendly software for all applications, both technical and business programming is now frequently carried out in C++.

Different programmers developed C++ from the programming language C. Although by no means a perfect language, C++ is, above all else, a flexible one, and it is available for all major computer systems on the market. At one level, C++ affords those who require it access to the underlying hardware of the computers which can be bettered only by much lower level assembly languages: such features means C++ can be use to build tools such as compilers and operating systems with relative ease. At another level, C++ can be viewed as a modern, block structured, high level language with excellent support for writing even the largest of programs. Moreover, writers of major networking software packages and database programs all provide easy ways for C++ programs to interact with their products (Pont 1996).

In short, used well, C++ can provide an efficient solution to virtually any programming task.

Object-oriented languages (Balagurusamy 1995)

Object-oriented programming is not the right of any particular language. Like structured programming, OOP concepts can be implemented using languages such as C and Pascal. However, programming becomes clumsy and may generate confusion when the programs grow large. A language that is specially designed to support the OOP concepts makes it easier to implement them.

The languages should support several of OOP concepts to claim that they are object-oriented. Depending upon the features they support, they can be classified into the following two categories:

- Object-based programming languages
- Object-oriented programming languages
- Object-based programming is the stile of programming that primarily supports encapsulation and object identity. Mayor features that are required for object-based programming are:
- Data encapsulation
- Data hiding and access mechanism
- Automatic initialisation and clear-up of objects
- Operator overloading

Languages that support programming with objects are said to be object-based programming languages. They do not support inheritance and dynamic binding. Abstract data type is a typical object-based programming language.

Object-oriented programming incorporates all of object-based programming features along two additional features, namely, inheritance and dynamic binding. Object oriented programming can therefore be characterised by the following statement:

Object-based features + inheritance + dynamic binding.

Languages that support these features include C++, Smalltalk and Object Pascal.

<u>Procedure-Oriented Programming</u> (Balagurusamy 1995)

Conventional programming using high level language such as COBOL, FORTRAN and C is commonly known as procedure-oriented programming. Procedure-oriented programming basically consists of writing a list of instructions for the computer follow, and organising these instructions into groups known as functions.

Some characteristics exhibited by procedure-oriented programming are:

- Emphasis is on doing things (algorithms).
- Large programs are divided into smaller programs known as functions.
- Most of the functions share global data.
- Data move openly around the system from function to function.
- Functions transform data from one from to another.
- Employs top-down approach in program design

<u>Object-oriented programming</u> (Balagurusamy 1995)

Object-oriented programming (OOP) treats data as a critical element in the program development and does not allow it to flow freely around the system. OOP allows us to decompose a problem into a number of entities called objects and then builds data and functions around these entities. OOP is an approach that provides a way of modularising programs by creating partitioned memory area for both data and functions that can be used as templates for creating copies of such modules on demand. The organisation of data and functions in OOP is shown in figure B.2.

Some of the striking features of object oriented programming are:

- Emphasis is on data rather than the procedure.
- Programs are divided into what are known as objects.
- Data structures are designed such that they characterise the objects.
- Functions that operate on the data of an object are tied together in the data structure.
- Data is hidden and cannot be accessed by external functions.

- Objects may communicate with each other through functions.
- New data and functions can be easily added whenever necessary.
- Follows bottom-up approach in program design.

Object-orientation contributes to the solution of many problems associated with the development and quality of software products. The new technology promise greater programmer productivity, better quality of software and lesser maintenance cost. The principal advantages are:

- Through inheritance, is possible to eliminate redundant code and extend the use of existing classes.
- We can build programs from the standard working modules that communicate with one another, rather than having to start writing the code from scratch. This leads to saving of development time and higher productivity.
- The principle of data hiding helps the programmer to built secure programs that cannot be invaded by code in other parts of the program.
- It is possible to have multiple instances of an object to co-exist with any interference.
- It is possible to map objects in the problem domain to those objects in the program.
- It is easy to partition the work in a project based on objects.
- The data-centred design approach enables us to capture more details of a model in implement able form.
- Object-oriented systems can be easily upgraded from small to large systems.
- Message passing techniques communications between objects makes the interface descriptions with external systems much simpler.
- Software complexity can be easily managed.

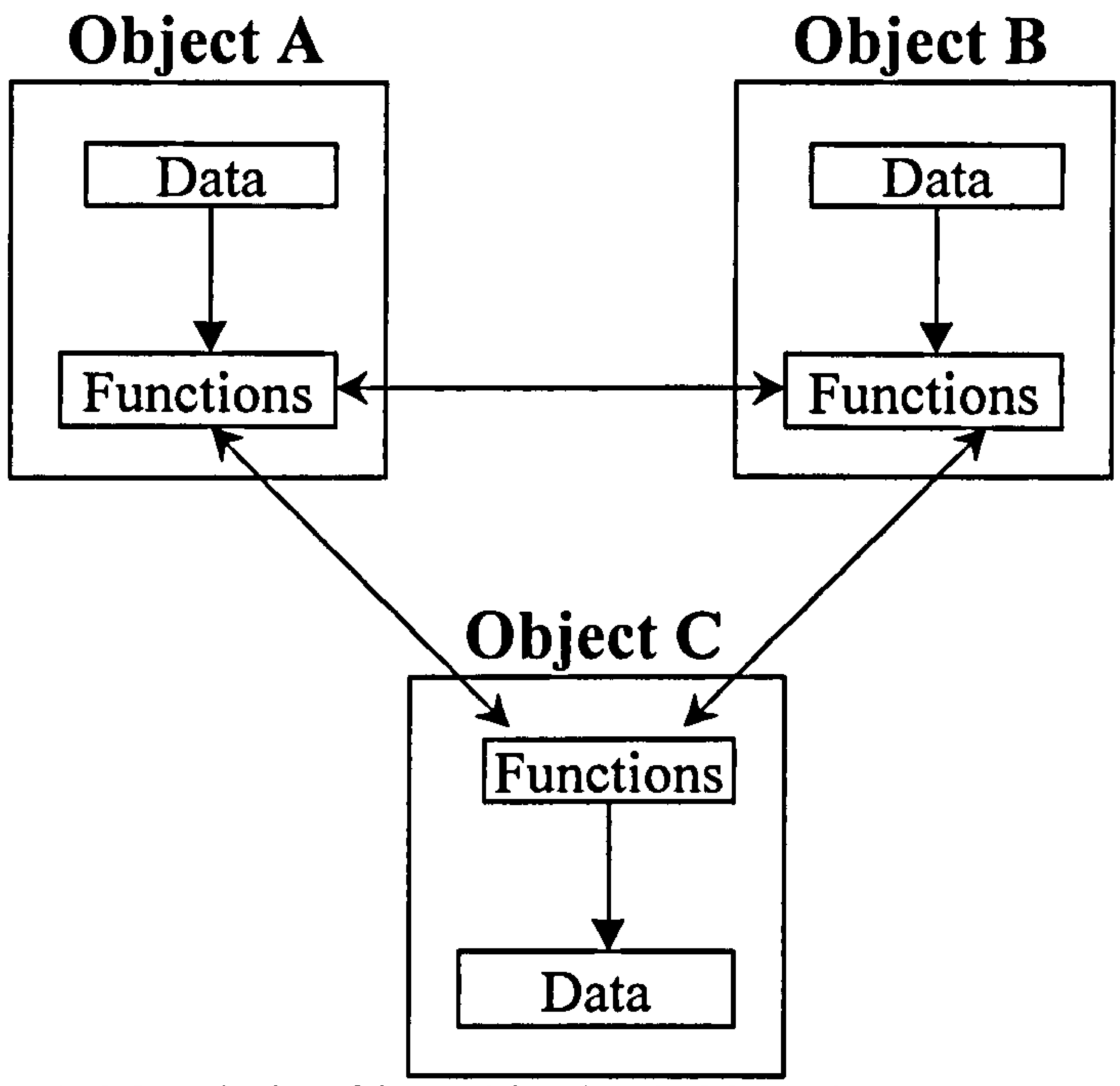


Figure A- 3 Organisation of data and functions in OOP (Balagurusamy 1995).

An important aspect of any program is its design: how to approach the development of the program. Object-oriented design is recognised as being a powerful technique, and the language C++ has the necessary facilities to allow object-oriented programming (Mitchell 1993).

A-3.2. OBJECT ORIENTED PROGRAMMING CONCEPTS

A-3.2.1. Objects

Objects are the basic run-time entities in an object-oriented system. They may represent a person, a place a bank account, a table of data or any item that the program must handle (Balagurusamy 1995).

Objects are an abstraction of something in a problem domain, reflecting the capabilities of the system to keep information about, interact with it, or both. An object is defined as a concept, abstraction, or thing with crisp boundaries and meaning for the problem at hand. Objects serve two purposes: They promote understanding of the real world and provide a practical basis for computer implementation (Bennett et al. 2002).

A-3.2.2. Classes

The entire set of data and code of an object can be made a user-defined data type with the help of a class. Each object is associated with the data of type class with which they are created. A class is thus a collection of objects of similar type. For example, mango apple and orange are members of the class fruit. If fruit has been defined as a class, then the statement.

Fruit mango;

Will create an object mango belonging to the class fruit.

A Class is a description of a set of objects that share the same attributes, operations, methods, relationships and semantics. Objects that are sufficiently similar to each other are said to belong to the same class. Instance is another word for a single object, but it also carries connotations of the class to which that object belongs: every object is an instance of some class. So, like an object an instance represents a single person, thing or concept in the application domain. A class is an abstract descriptor for a set of instances with certain logical similarities to each other (Bennett et al. 2002).

A-3.2.3. Data Encapsulation

The wrapping up of data and functions into a single unit (called class) is known as encapsulation. Data encapsulation is the most striking feature class. The data is not accessible to the out side world and only those functions which are wrapped in the class can access it. This insulation of the data from direct access by program is called data hiding. (Balagurusamy E., 1995)

A-3.2.4.Data Abstraction

Abstraction refers to the act of presenting essential features without including the background details or explanations. Classes use the concept of abstraction and are defined as a list of abstract attributes such as size, weight and cost, and functions to operate on these attributes. They encapsulate all the essential properties of the objects that are to be created. Since the classes use the concept of data abstraction, they are known as Abstract Data Types (ADT) (Balagurusamy 1995).

Abstraction is a form of representation that includes only what is important or interesting from a particular viewpoint. For example, a map is an abstract representation (Bennett et al. 2002).

A-3.2.5. Inheritance

Inheritance is the process by which objects of one class acquire the properties of objects of another class. It supports the concept of hierarchical classification. Each derived class shares common characteristics with the class from which is derived. Each sub class defines only those features that are unique to it. Without the use of classification, each class would have to explicitly include all of its features (Balagurusamy 1995).

Inheritance is a mechanism for implementing generalisation and specialisation in an object-oriented programming language (see figure B.3). When two classes are related by the mechanism of inheritance, the more general class in called a super class in relation to the other, and the more specialised is called subclass. The rules of object-oriented inheritance are: a subclass inherits all the characteristics of its super class, b) the definition of subclass always includes at least one detail not derived from its super class (Bennett et al. 2002).

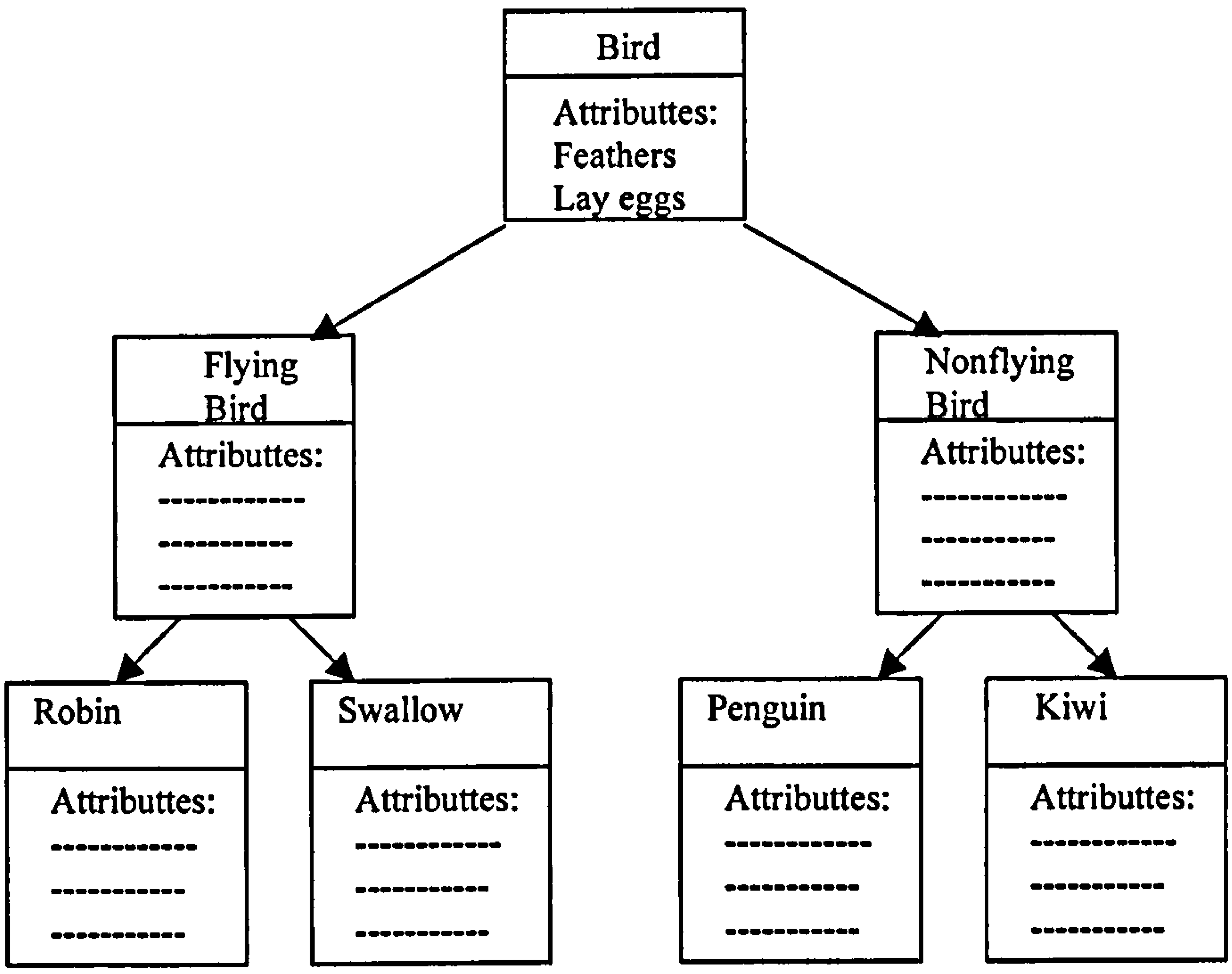


Figure A- 4 Property Inheritance (Balagurusamy 1995)

A-3.2.6. Polymorphism

Polymorphism means the ability to take more that one form. Polymorphism plays an important role in allowing objects having different internal structures to share the same external interface (see figure B4). Polymorphism is extensively used in implementing inheritance (Balagurusamy 1995).

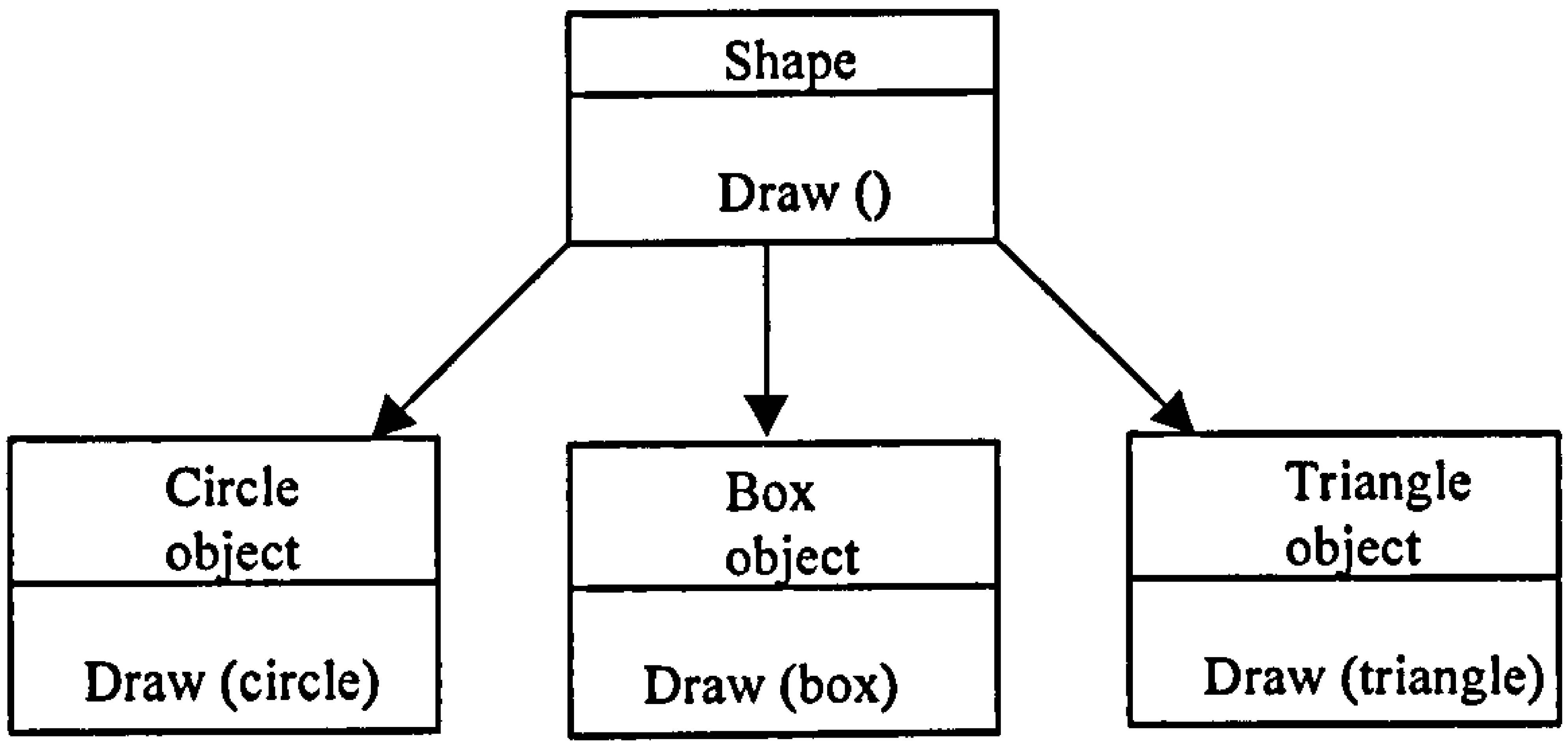


Figure A- 5 Polymorphism (Balagurusamy 1995)

When one person sends a message to another, it is often convenient to ignore many of the differences that exist between the various people that might receive the message. Polymorphism literally means 'an ability to appears as many forms', and its refers to the possibility of identical messages being sent to objects of different classes, each of which responds to the message in a different, yet still appropriate way. This means the originating object does not need to know which class is going to receive the message on any particular occasion. The key to this is that a receiving object is responsible for knowing how to respond to messages (Bennett et al. 2002).

A-3.2.7. Dynamic Binding

Binding refers to the link of a procedure call to the code to be executed in response to the call. Dynamic binding means that the code associated with a given procedure call is not known until the time of the call at run-time (Balagurusamy 1995).

A-3.2.8. Message communication

An object-oriented program consists of a set of objects that communicate with each other. The process of programming in an object-oriented language therefore involves the following basic steps (Balagurusamy 1995):

a) Creating classes that define objects and their behaviour.

b) Creating objects from class definitions.

c) Establishing communication among objects.

A message for an object is a request for execution of a procedure, and therefore will invoke a function (procedure) in the receiving object that generates the desired result.

A-3.3. ARRAYS

An array is used to process a collection of data, all of which is of the same type: such as a list of test scores, a list of temperature, or a list of names. An array is very much like a list of variables, each of which has two-part name. One part of the name is the same for each of the variables that collectively constitute the array. For example, the names for the five individual variables we need might be score[1], score[2], score[3], score[4], score[5]. The part that doesn't chance, in this case score, is the name of the array. The part that can be chance is the integer in the square brackets [ ]. Each variable used so far corresponds to only one number (or one character). With many programming problems we want to use a sequence of numbers (or other objects), the elements of which have the same name and are distinguished by an integer 0,1,2,3... We can do this by using arrays (Savitch 1996).

A-3.4. POINTERS

A pointer is a construct that gives you more control of the computer's memory. Dynamic arrays are arrays whose size is determined while the program is running, rather than being fixed when the program is written. A pointer is the memory address of a variable. A pointer can be stored in a variable. However, even though a pointer is a memory address and a memory address is a number, you cannot store a pointer in a variable of type int or double. A variable to hold a pointer must be declared to have a pointer type (Savitch 1996).

This appendix presents the information and knowledge required to support the next process planning decisions.

- Stock selection.

- Process selection.

- Machine selection.

- Set up.

The information and knowledge to support the above decisions were used in the experiments to test and validate the research ideas.

B-1. Information and knowledge to produce a process plan to manufacture sample I

Sample I

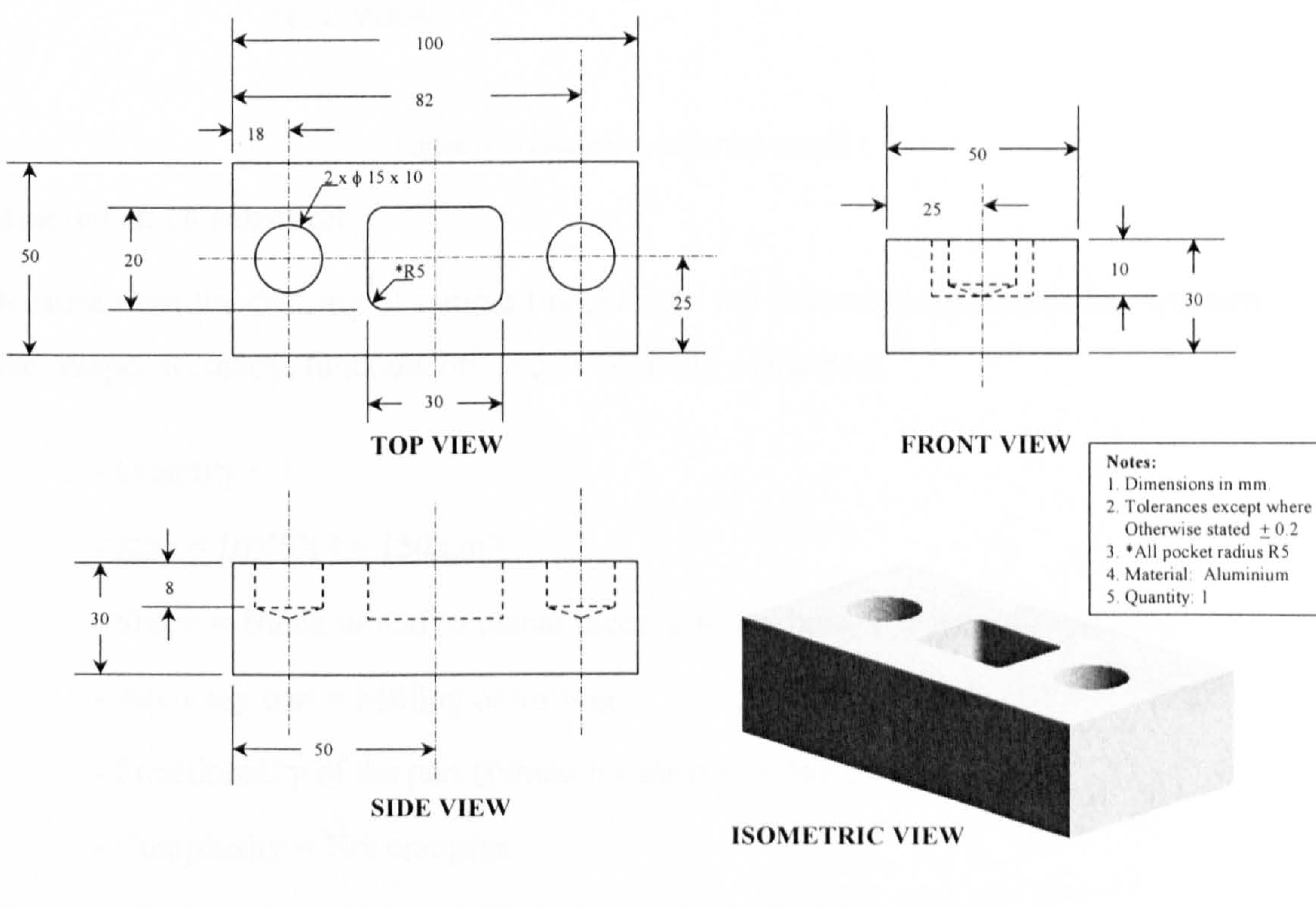


Figure B- 1 Sample I design data

F1,F2,F3,F4,F5,F6: (6) Planar faces
F7,F8: (2) Blind end round holes
F9: (1) Blind rectangular close pocket

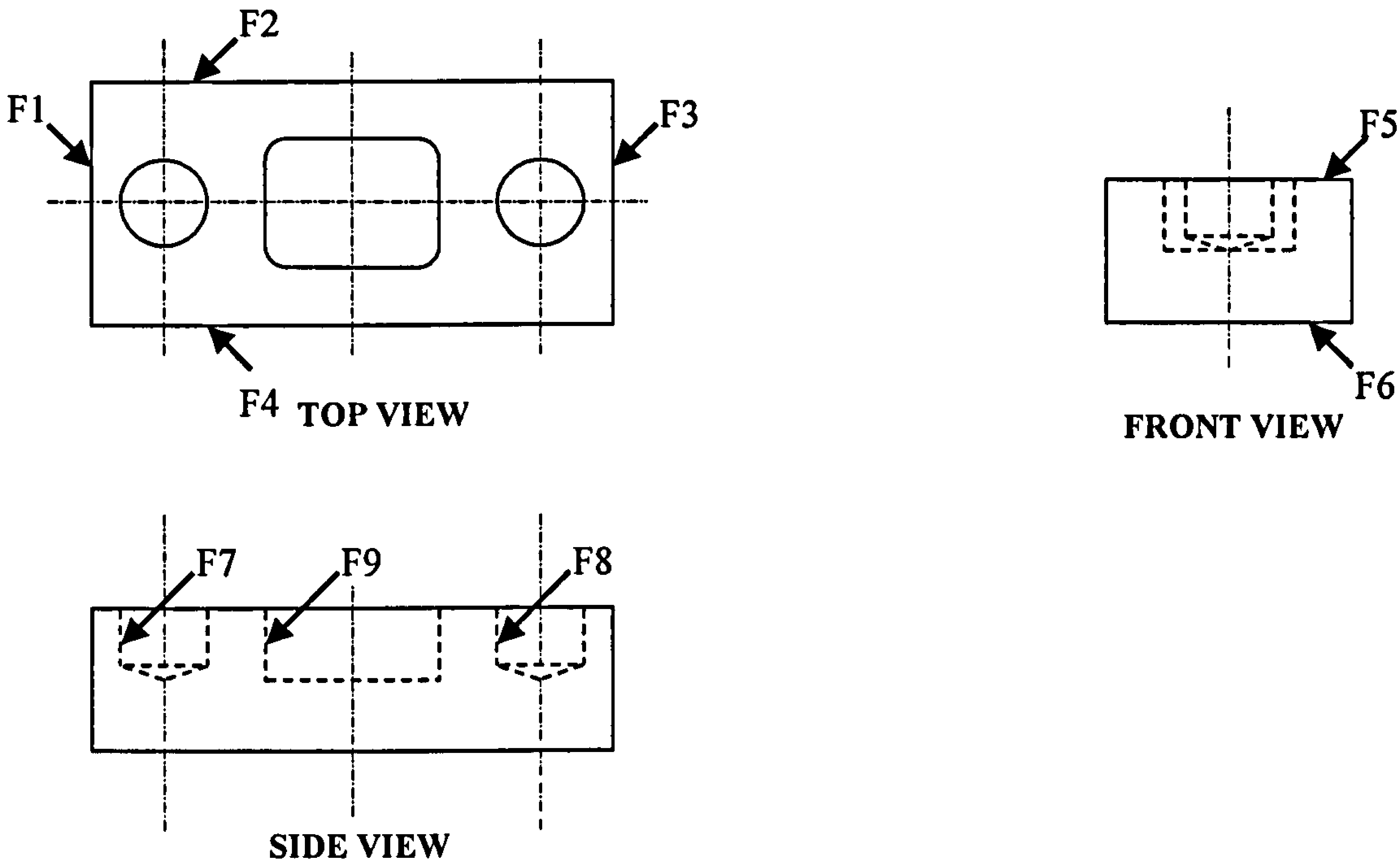


Figure B- 2 Feature identification sample I

Material stock selection

Because from the drawing of sample I is obtained the following characteristics: Quantity, size, shape, accuracy, functionality and complexity of the part.

- Quantity = 1
- Size = 10X5X3 = 150 cm3
- Shape = Block mould (6 planar faces, 2 round hole, 1 rectangular pocket)
- Accuracy part = Milling or turning
- Functionality of the part (fitness for purpose): Not critical
- Complexity = Not complex

Then standard stock should most likely be used. In addition, because the part shape is rectangular, then a **standard rectangular bar** should most likely be used.

Criteria applied to Material stock selection

High quantity (quantity>5,000) and/or large sizes (size>6750 cm3)= Casting

"Main criteria (Material Cost Reduction)"

Complex regular geometry and/or Complex irregular geometries and complicated cavities = Casting

"Main criteria (Process capability)"

Other case standard

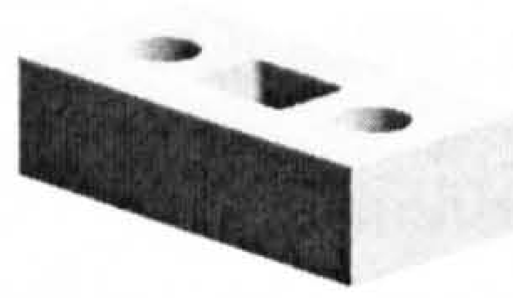
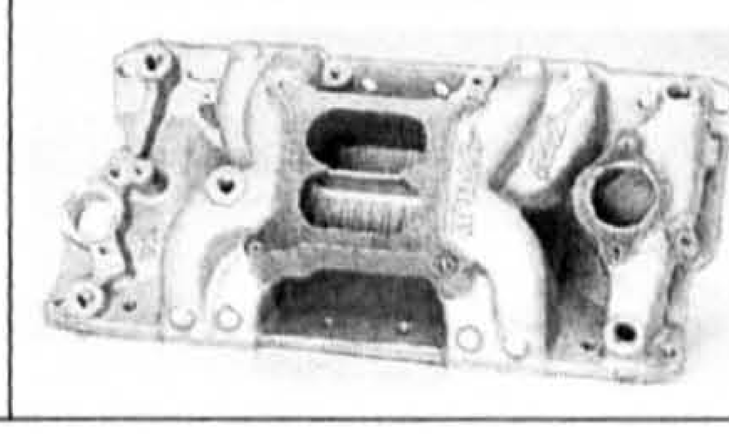
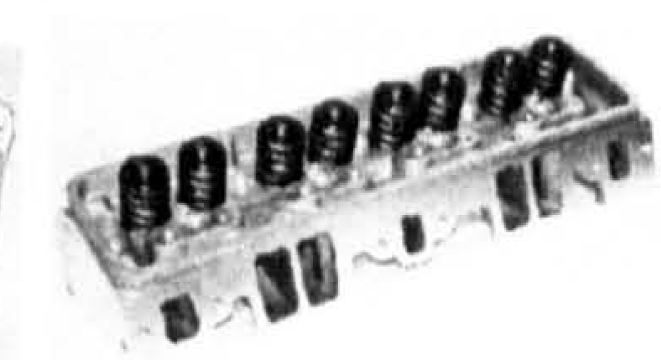
Regular geometry		Irregular geometries and complicated cavities
Not complex	Complex	Complex
Example: 	An example is the same not complex regular geometry but with some following features: • Angular faces •Tapered holes •Tapered pockets	 

Figure B- 3 Examples of different shape complexities (regular, irregular geometries and complicated part cavities)

Typical roughness values obtained by different finishing processes [Source: ISO 1302:2001]

- Roughness (Ra) in mm

Milling 0.8 <Ra< 6.3

Drilling 1.6 <Ra< 6.3

Boring 0.4 <Ra< 6.3

Turning 0.4 <Ra< 6.3

Grinding 0.1 <Ra< 6.3

Process selection

Because from the drawing of sample I is obtained the following characteristics:

- Shape = Block mould (6 planar faces, 2 blind end round holes, 1 rectangular pocket)
- Accuracy tolerance = Milling or turning
- The part is not a rotational component

Then a **milling process** should most likely be used.

Machine selection

Because from the drawing of sample I is obtained the following characteristics:

- Quantity = 1
- Complexity = Not complex
- Working range = Low (speed, size, feed, weight)

Then a **three axes milling machine** should most likely be used.

Set ups

Because pre-cut standard rectangular bar is used and considering:

- Quantity, size, shape, accuracy, functionality and complexity of the part.
- The number, shape and accuracy of features to be produced.
- The shop resources.

Then a minimum of 1,4 or 6 set ups is required depending on the following scenarios:

If the material stock selection:

- Is a standard rectangular bar of 50X30 mm with acceptable dimensional tolerance + 0.2

Has been cut through F1 and F3

F2,F4,F5,F6 planar faces have acceptable roughness values in order to avoid machining

Then scenario A, other case scenario B or scenario C

Scenario A (One setup)
Setup 1: - Locate workpiece in vice using F2 and F4 to hold it, letting F1, F3 and F5 free to machining - Face F1 to 50 X 30 mm - Face F3 to 50 X 30 mm - Drill the 2 blind end holes F7, F8 - Produce the blind rectangular close pocket F9

Figure B- 4 Set up to sample I, scenario A

Scenario B (Four setups)

Setup 1:
- Locate workpiece in vice
- Face F6 to 100 X 50 mm

Setup 2:
- Locate workpiece in vice
- Face F2 to 100 X 30 mm

Setup 3:
- Locate workpiece in vice
- Face F4 to 100 X 30 mm

Setup 4:
- Locate workpiece in vice
- Face F1 to 50 X 30 mm
- Face F3 to 50 X 30 mm
- Face F5 to 100 X 50 mm
- Drill the 2 blind end holes F7, F8
- Produce the blind rectangular close pocket F9

Figure B- 5 Set ups sample I, scenario B

Scenario C (Six setups)

Setup 1:
- Locate workpiece in vice
- Face F1 to 50 X 30 mm

Setup 2:
- Locate workpiece in vice
- Face F2 to 100 X 30 mm

Setup 3:
- Locate workpiece in vice
- Face F3 to 50 X 30 mm

Setup 4:
- Locate workpiece in vice
- Face F4 to 100 X 30 mm

Setup 5:
- Locate workpiece in vice
- Face F6 to 100 X 50 mm

Setup 6:
- Locate workpiece in vice
- Face F5 to 100 X 50 mm
- Drill the 2 blind end holes F7, F8
- Produce the blind rectangular close pocket F9

Figure B- 6 Set ups sample I, scenario C

B-2. Information and knowledge to produce a process plan to manufacture sample II

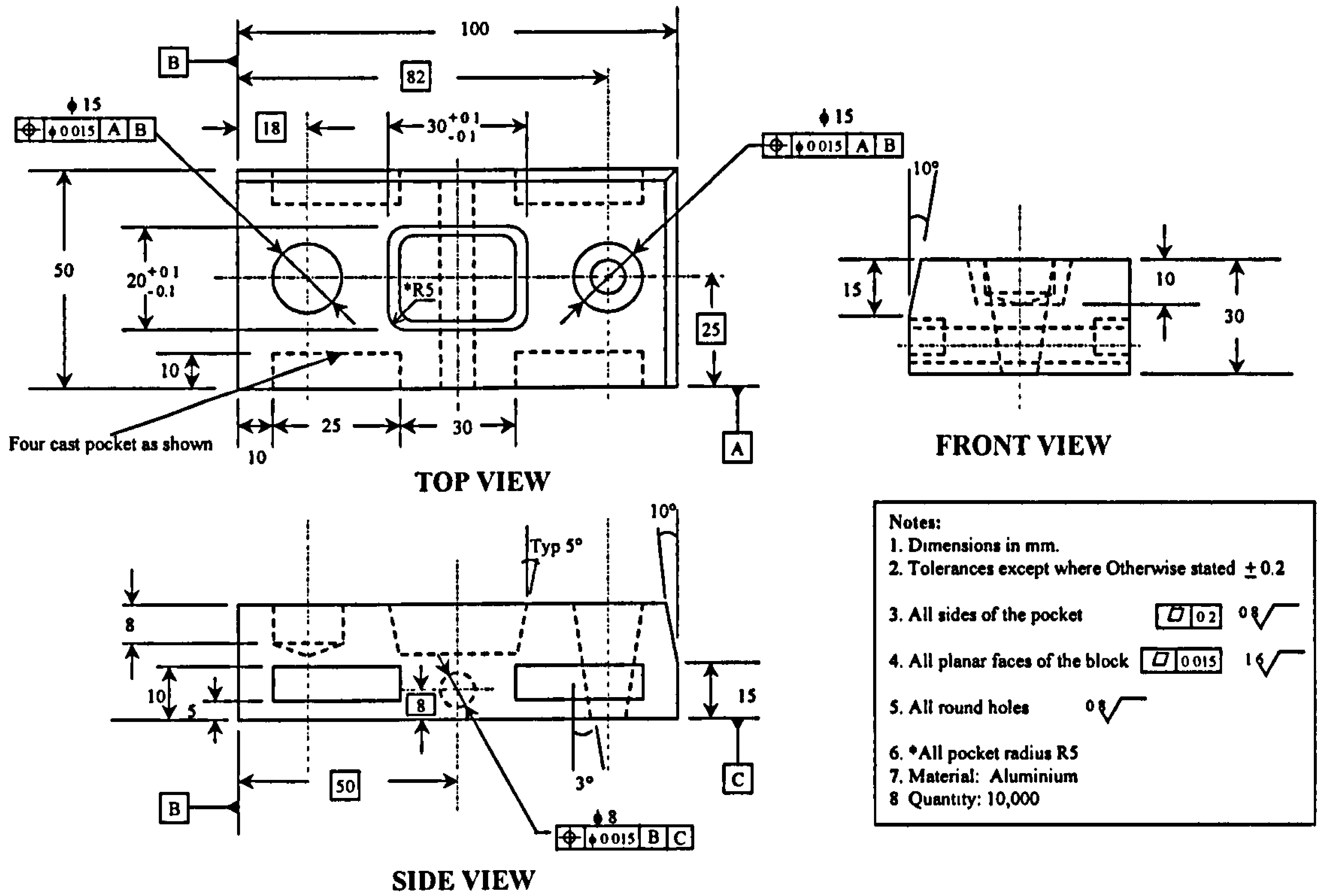


Figure B- 7 Sample II design data

Material stock selection

Because from the drawing of sample II is obtained the following characteristics:

- Quantity, size, shape, accuracy, functionality and complexity of the part.
  - Quantity = 10,000.
  - Size = 10X5X3 = 150 cm3.
  - Shape = Block mould (4 perpendicular planar faces, 2 angular faces, 3 round holes (1 blind end, 1 through end, 1 tapered), 1 tapered-blind end-rectangular-closed pocket 4 blind end-rectangular-open pockets).
  - Accuracy part = Grinding
  - Functionality of the part (fitness for purpose): Cavity obtained from the tapered-blind end-rectangular-closed pocket will be used as injection moulding cavity.
  - Complexity = Complex

Then **casting** should most likely be used.

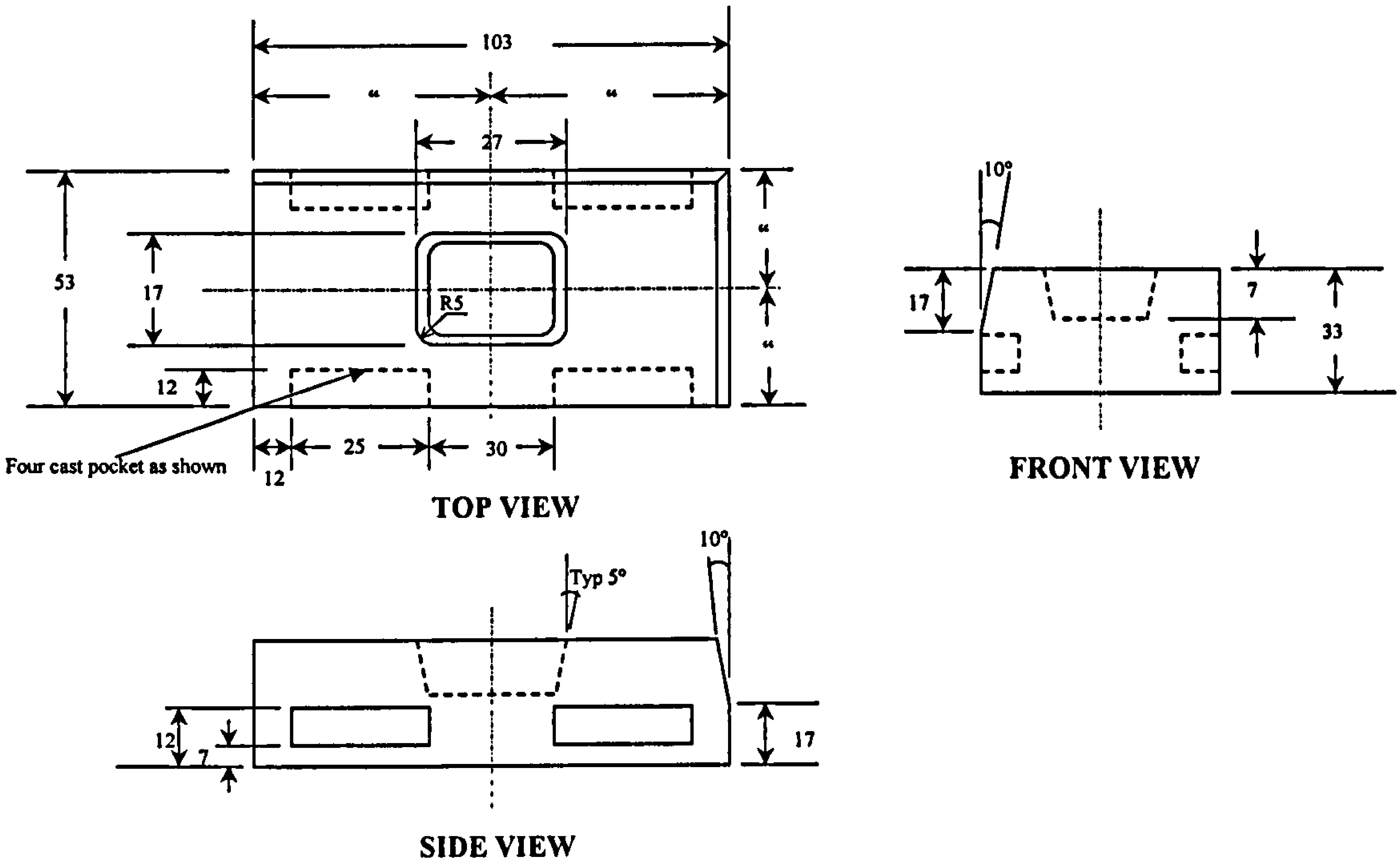


Figure B- 8 Possible casting sample II

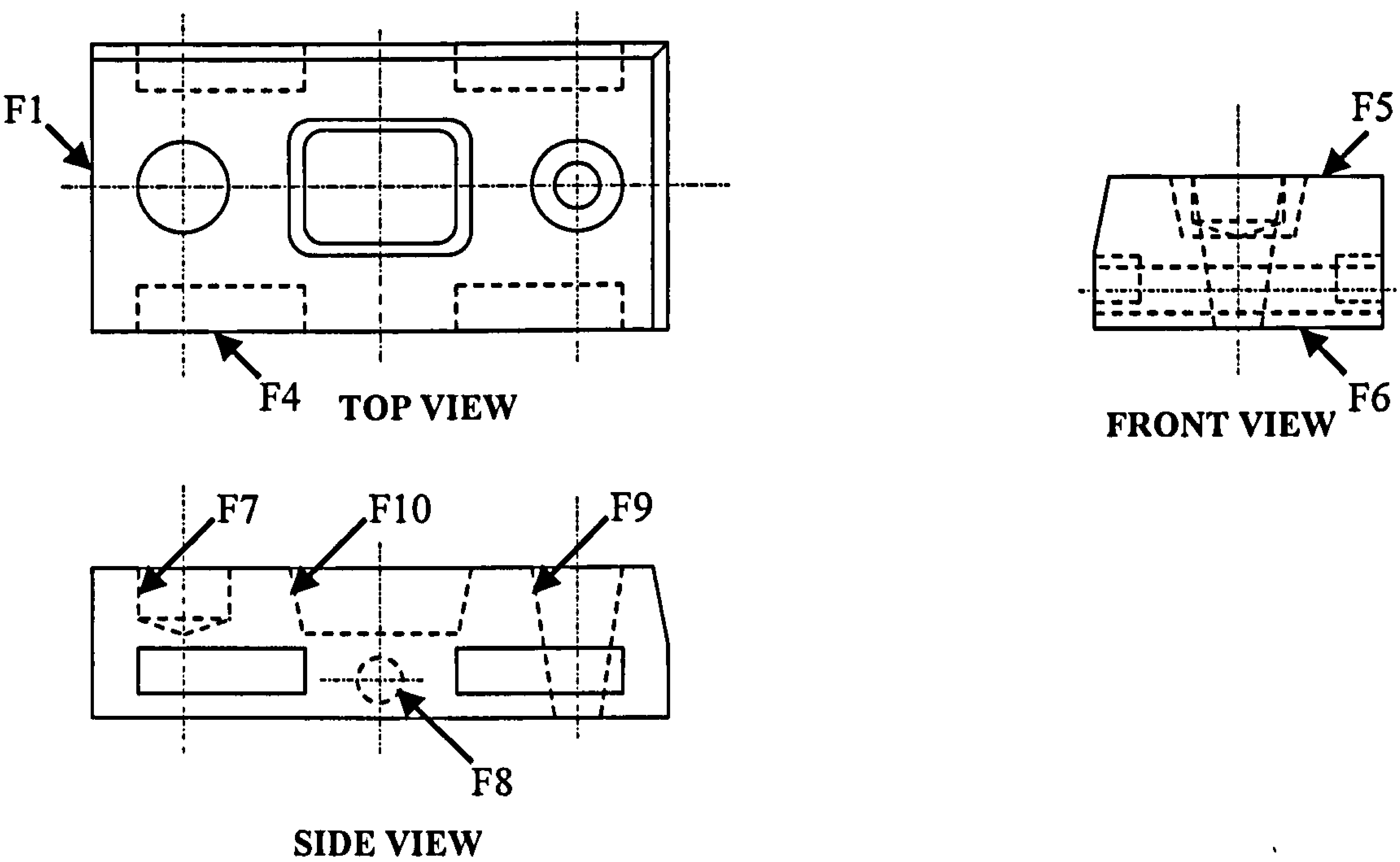


Figure B- 9 Features to be machined for sample II

Features:

F1,F4,F5,F6: (4) Planar faces

F7: (1) Blind end round hole

F8: (1) Through end round hole

F9: (1) Tapered round hole

F10: (1) Tapered blind end rectangular closed pocket

Process selection

Because from the drawing of sample II is obtained the following characteristics:

- The part is not a rotational component
- Shape = Block mould (4 perpendicular planar faces, 2 angular faces, 3 round holes (1 blind end, 1 through end, 1 tapered) , 1 tapered-blind end-rectangular -closed pocket
  4 blind end-rectangular-open pockets).
- Accuracy tolerance
  - F1,F4,F5,F6 ⏥ 0.015 1.6√
  - F7-F9 0.8√
  - F10 ⏥ 0.2 0.8√

Then the process that should most likely be used are:

- **Milling**
- **Turning**
- **Grinding**

Machine selection

Because from the drawing of sample II is obtained the following characteristics:

- Quantity = 10,000 piece.
- Complexity = Complex
- Working range = Low (speed, size, feed, weight)

Then the machines that should most likely be used are:

- **Grinding machine**
- **Milling machine four axes**
- **Lathe**

Set ups

Because casting is used and considering:

- Quantity, size, shape, accuracy, functionality and complexity of the part

- The number, shape and accuracy of features to be produced.

- The shop resources.

Then **a minimum of 10 set ups is required.**

Set up 1:

Milling

- Use modular fixture in 4 axes machine and locate 16 work pieces.

- Face F6 to 100 X 50 mm. Leave tolerances for grinding.

Set up 2:

Milling

- Use modular fixture in 4 axes machine and locate 24 work pieces.

- Face F1 to 50 X 30 mm. Leave tolerances for grinding

Set up 3:

Milling

- Use modular fixture in 4 axes machine and locate 24 workpieces.

- Face F4 to 100 X 30 mm. Leave tolerances for grinding

- Rough drill F8

Set up 4:

Milling

- Use modular fixture in 4 axes machine and locate 16 work pieces.

- Face F5 to 100 X 50 mm. Leave tolerances for grinding.

- Rough drill F7, [F9 pilot hole] and rough pocket F10

- Remove the part and move it to a grinding machine

Set up 5:
Grinding
- Locate 4 workpieces on magnetic table.
- Grind Face F6 to [▱ | 0 015] and 30mm dimension.

Set up 6:
Grinding
- Locate 4 workpieces face F6 to angle block.
- Grind Face F4 to [▱ | 0 015] and 50mm dimension.

Set up 7:
Grinding
- Locate 4 workpieces on to angle block and ensure F6 and F4 are perpendicular to machine axes.
- Grind Face F1 to [▱ | 0 015] and 100mm dimension.
- Remove the part and move it to the milling press.

Set up 8:

Milling

- Use modular fixture in 4 axes machine and locate 24 work pieces.

- Set origin on datum surfaces

- Bore through end hole F8

Set up 9:

Milling

- Use modular fixture in 4 axes machine and locate 16 work pieces.

- Set origin on datum surfaces.

Bore blind hole F7

Bore [pilot hole F9]

Produce tapered blind rectangular closed pocket F10

Remove the part and move it to the lathe.

Set up 10:

Turning

- Locate part on dedicated fixture

- Turn tapered hole F9

B-3. Information related to the two work shops

Shop1: Advanced Technology Manufacturing Centre

Resource:

- Three CNC machine centres that are two three-axis verticals and one four axes horizontal respectively.
- Two CNC lathes.
- CAD/CAM system.
- Tooling library containing milling, drilling, reaming, boring and turning tools and holders.
- Standard work holding fixtures and modular fixturing system
- Material store
- One skill CNC programmer operator

Process:

Milling process, drilling process, boring process, reaming process and turning process

Manufacturing knowledge:

Explicit, tacit and implicit process planning knowledge to take the following decisions: Material stock selection, process selection, machine selection and set ups

Shop2: Engineering Application Laboratory

Resource:

- Three manual milling machines: two three-axis verticals and one three-axis horizontal.	- One fitting/assembly area.
- One jig boring machine.	- Tooling library containing milling, drilling, reaming, boring and turning tools and holders.
- One manual drilling machine.	- Standard work holding fixtures
- Five manual lathes.	- Grinding wheels
- One surface-grinding machine.	- Material store
- One power saw and one band saw.	- 3 skilled machine operators.

Process:

Milling process, drilling process, boring process, reaming process, turning process and grinding process

Manufacturing knowledge:

Explicit, tacit and implicit process planning knowledge to take the following decisions: Material stock selection, process selection, machine selection and set ups

APPENDIX C. UML Class Diagrams Representation

- **C-1. Manufacturing Facility Information and Knowledge Model Structures**

    Figure C-1-1. MFIKM Main Structure

    Figure C-1-2. Process Knowledge Structures

    Figure C-1-3. Resource Knowledge Structure

    Figure C-1-4. Types of Knowledge Structure

    Figure C-1-5. Process Information Structure

    Figure C-1-6. Resource Information Structure

    Figure C-1-7. Facility Information Structure

- **C-2. Product Model Structures**

    Figure C-2-1. Product Model Structures

Figure C-1-1. Manufacturing Facility Information and Knowledge Main Structures

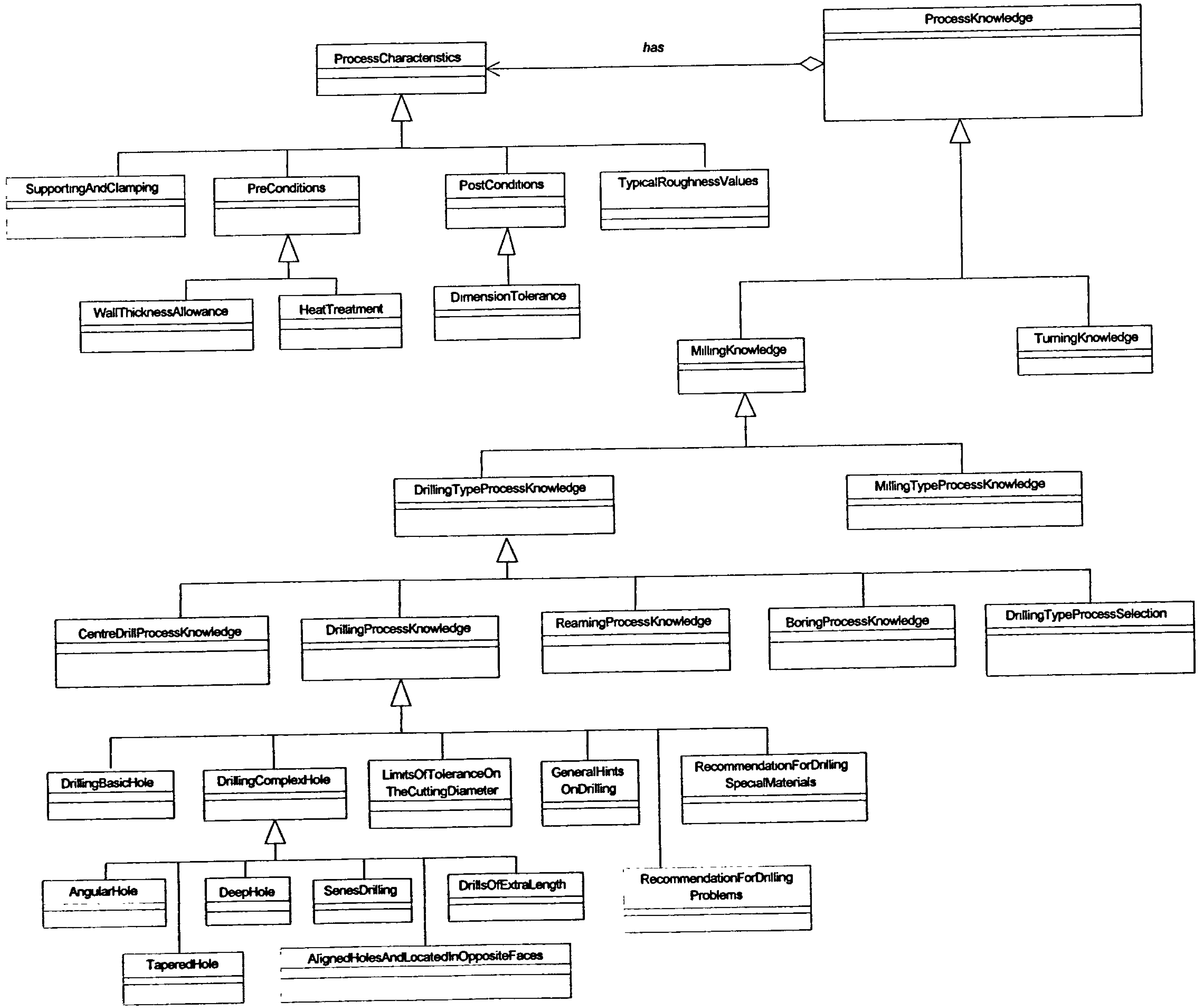


Figure C-1-2. Process Knowledge Structure

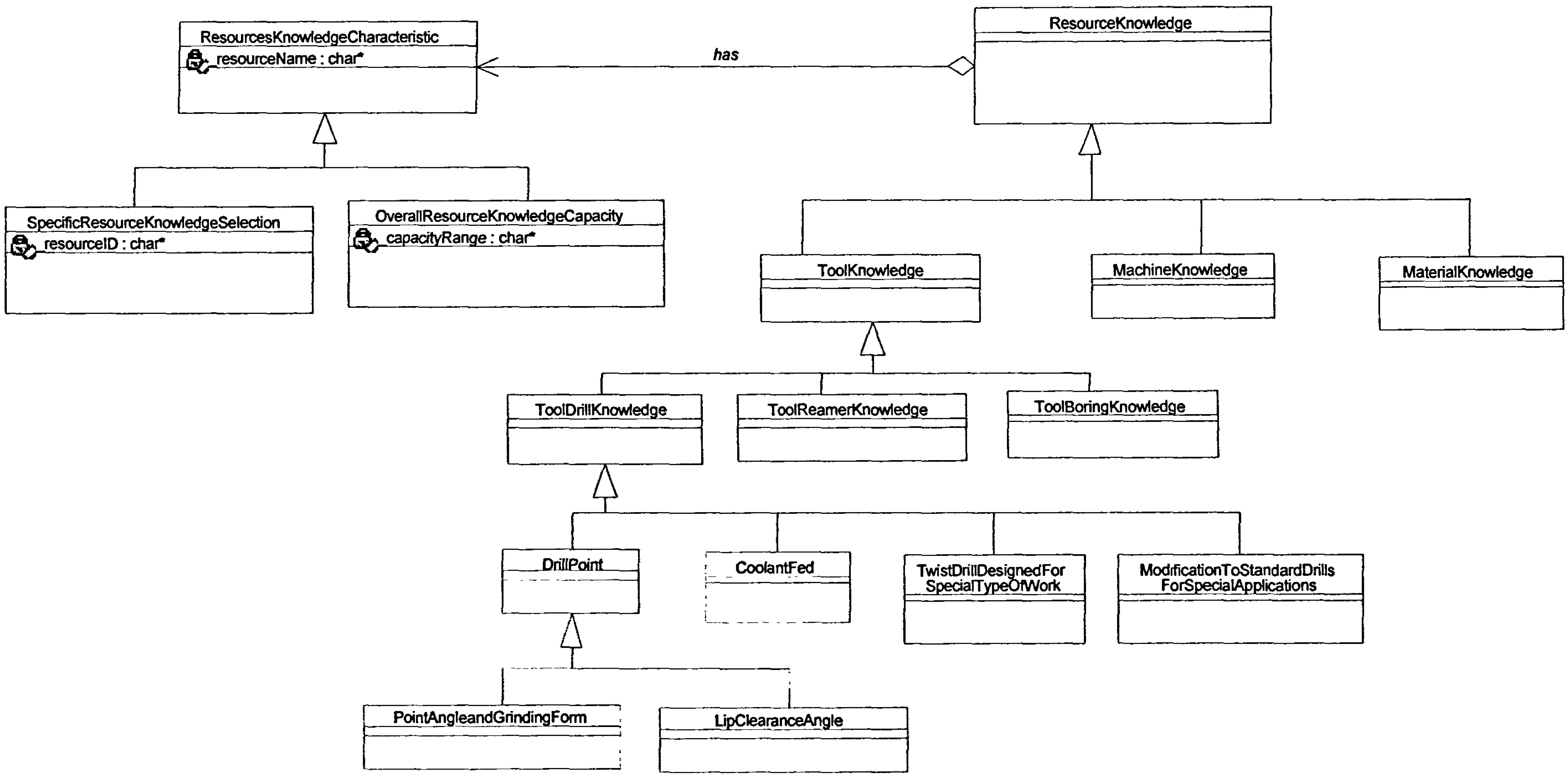


Figure C-1-3. Resource Knowledge Structure

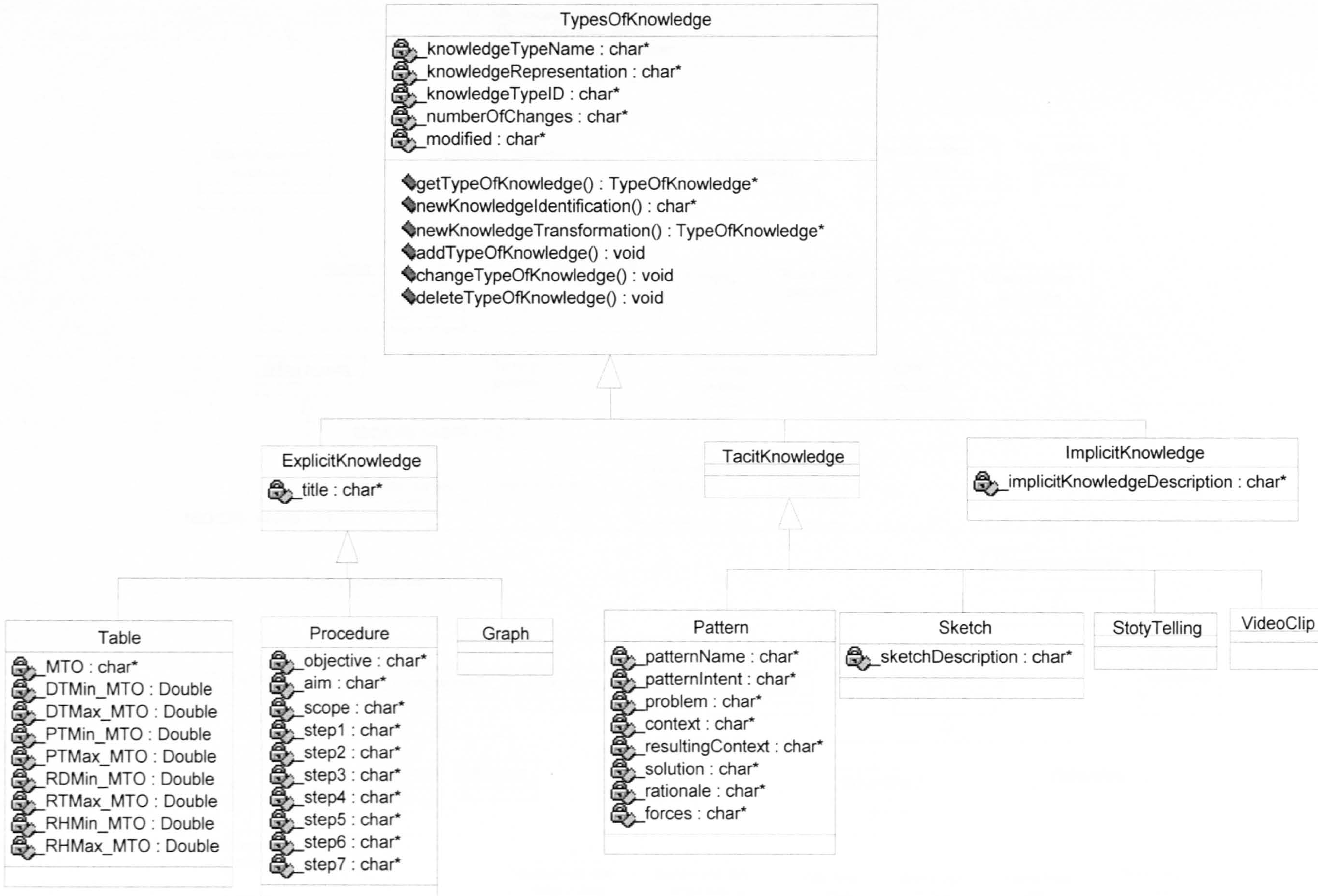


Figure C-1-4. Types of Knowledge Structure

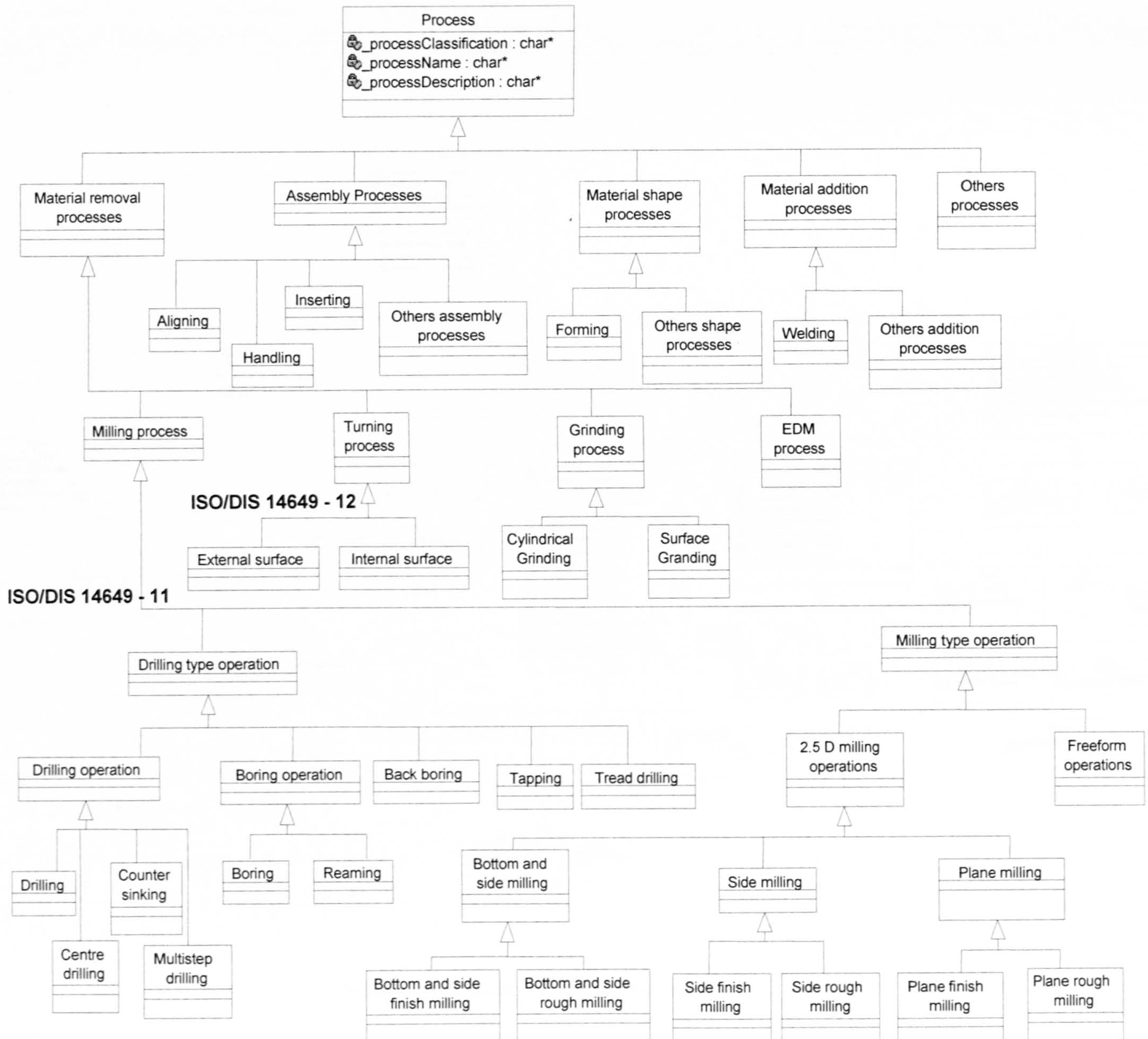


Figure C-1-5. Process Information Structure

Figure C-1-6. Resource Information Structure

Figure C-1-7. Facility Information Structure (Molina, Ellis et al. 1995), (Zhao, Cheung et al. 2000)

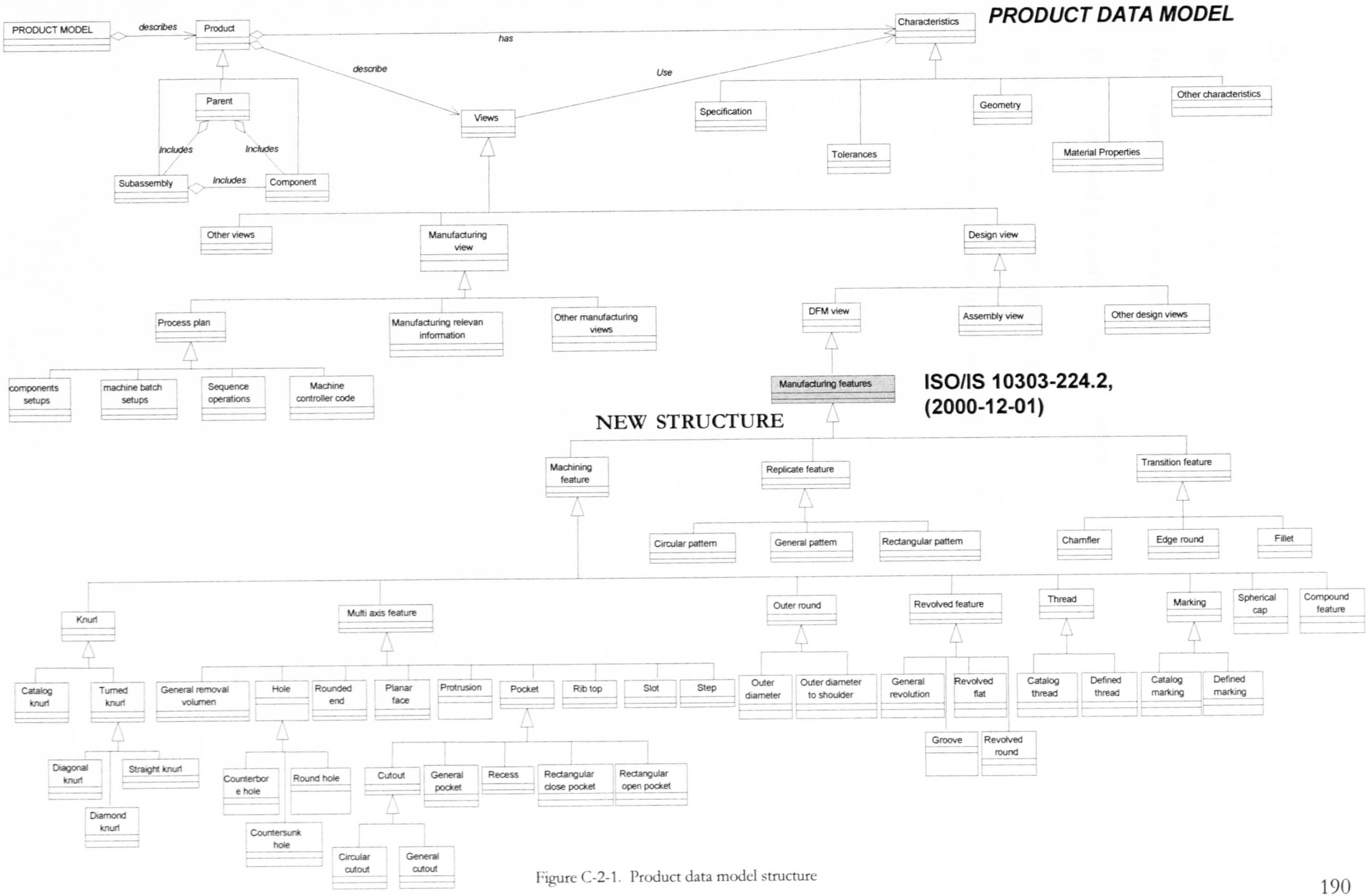


Figure C-2-1. Product data model structure

D-1. Information population into MFIKM

D-2. Knowledge population into MFIKM

D-3. Information maintenance in MFIKM

D-4. Knowledge maintenance in MFIKM

D-5. Manufacturing support decisions, tapered round hole (002)

D-6. Knowledge instances change into MFIKM

D-1. Information population into MFIKM

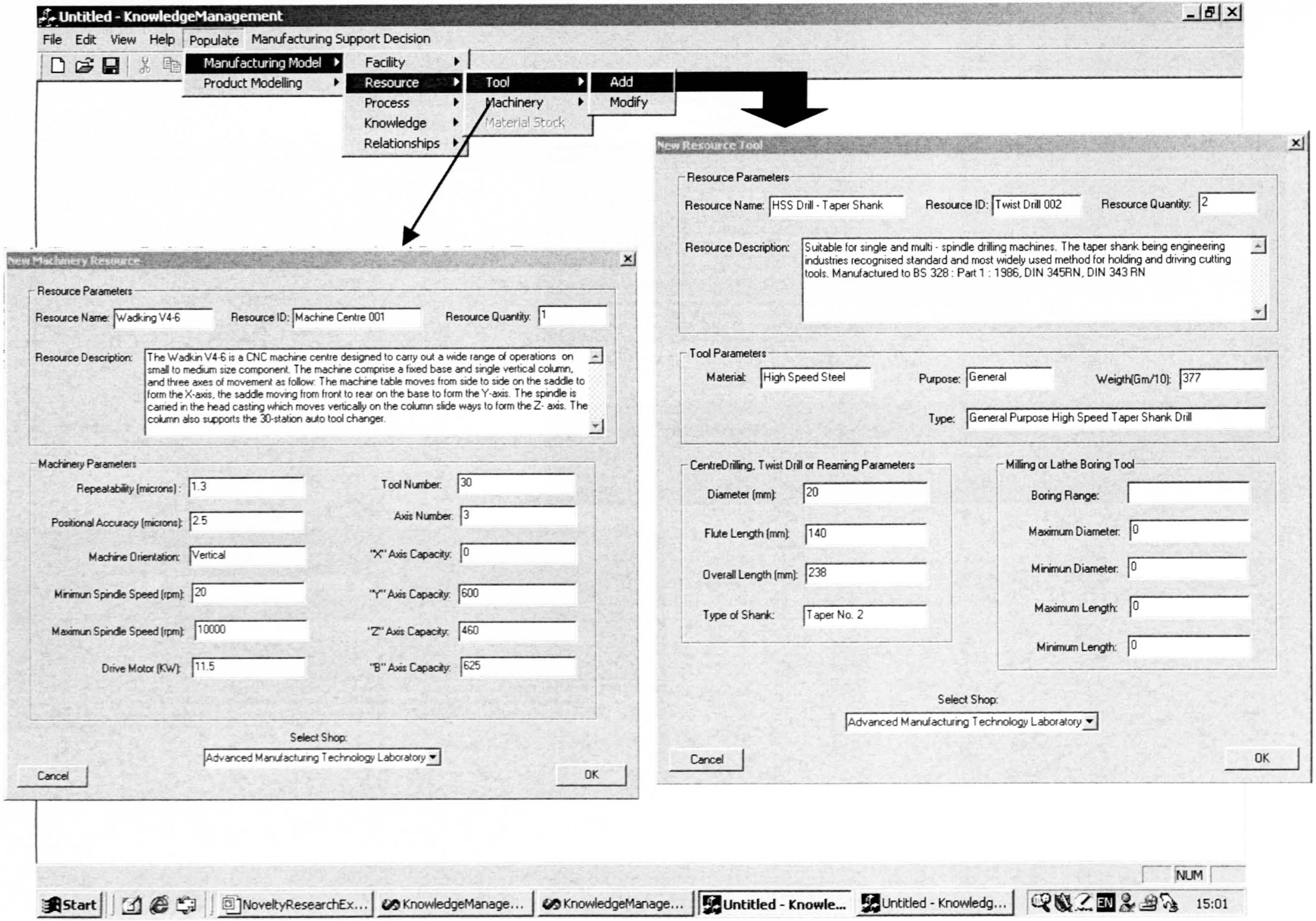


Figure D-1 Resource information population into MFIKM

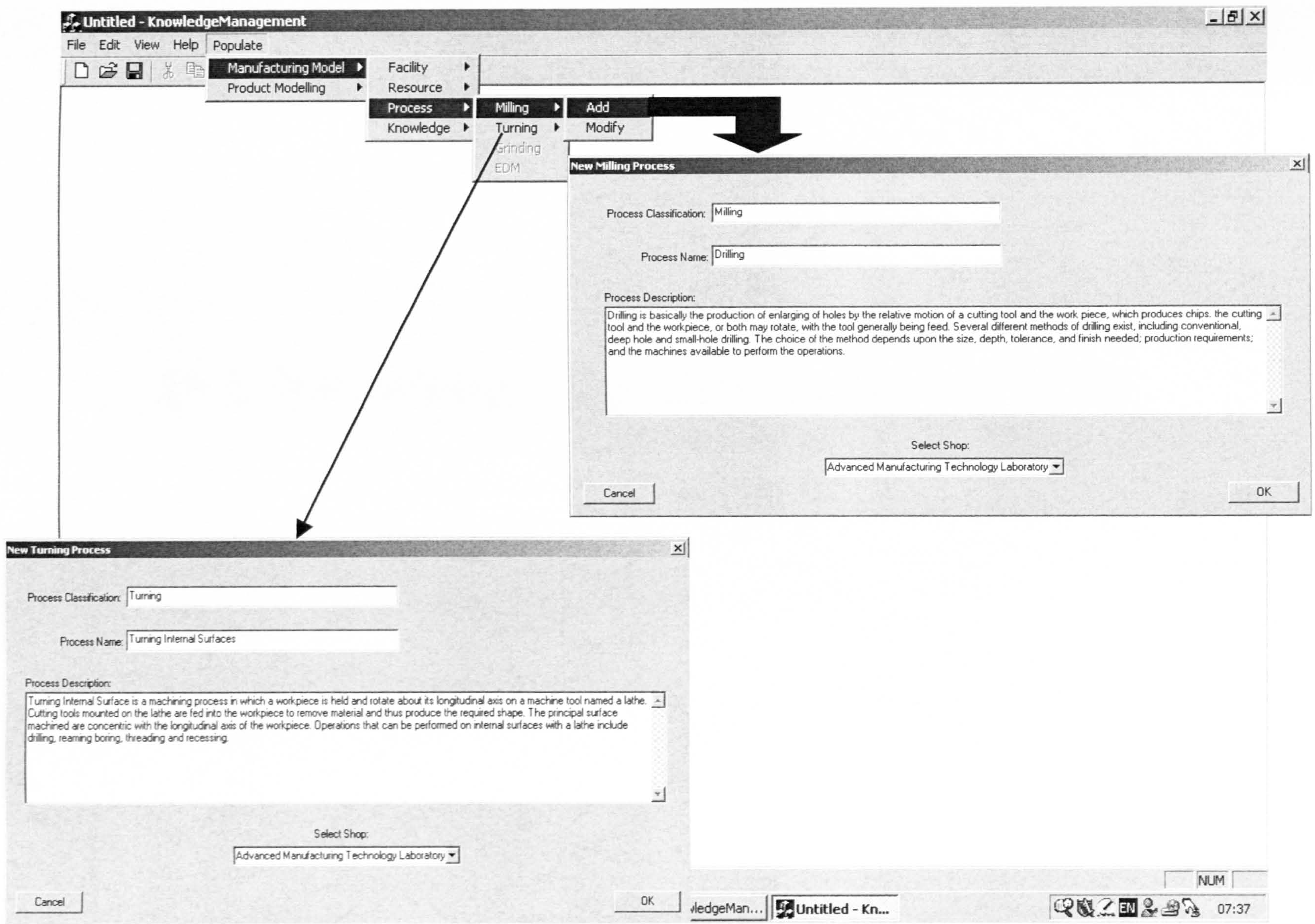


Figure D-2 Process information population into MFIKM

D-2. Knowledge population into MFIKM

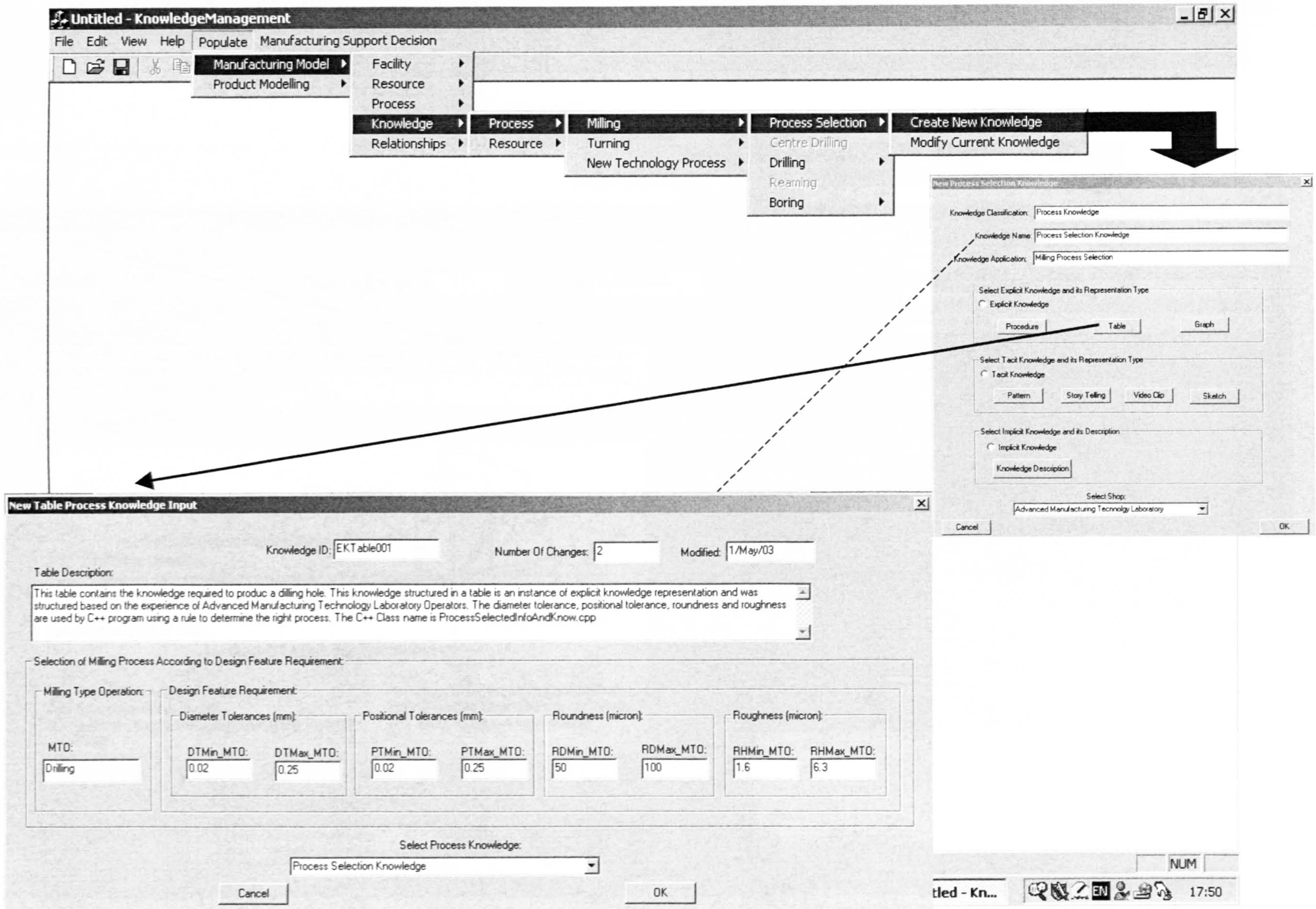


Figure D-3 Process selection knowledge population into MFIKM

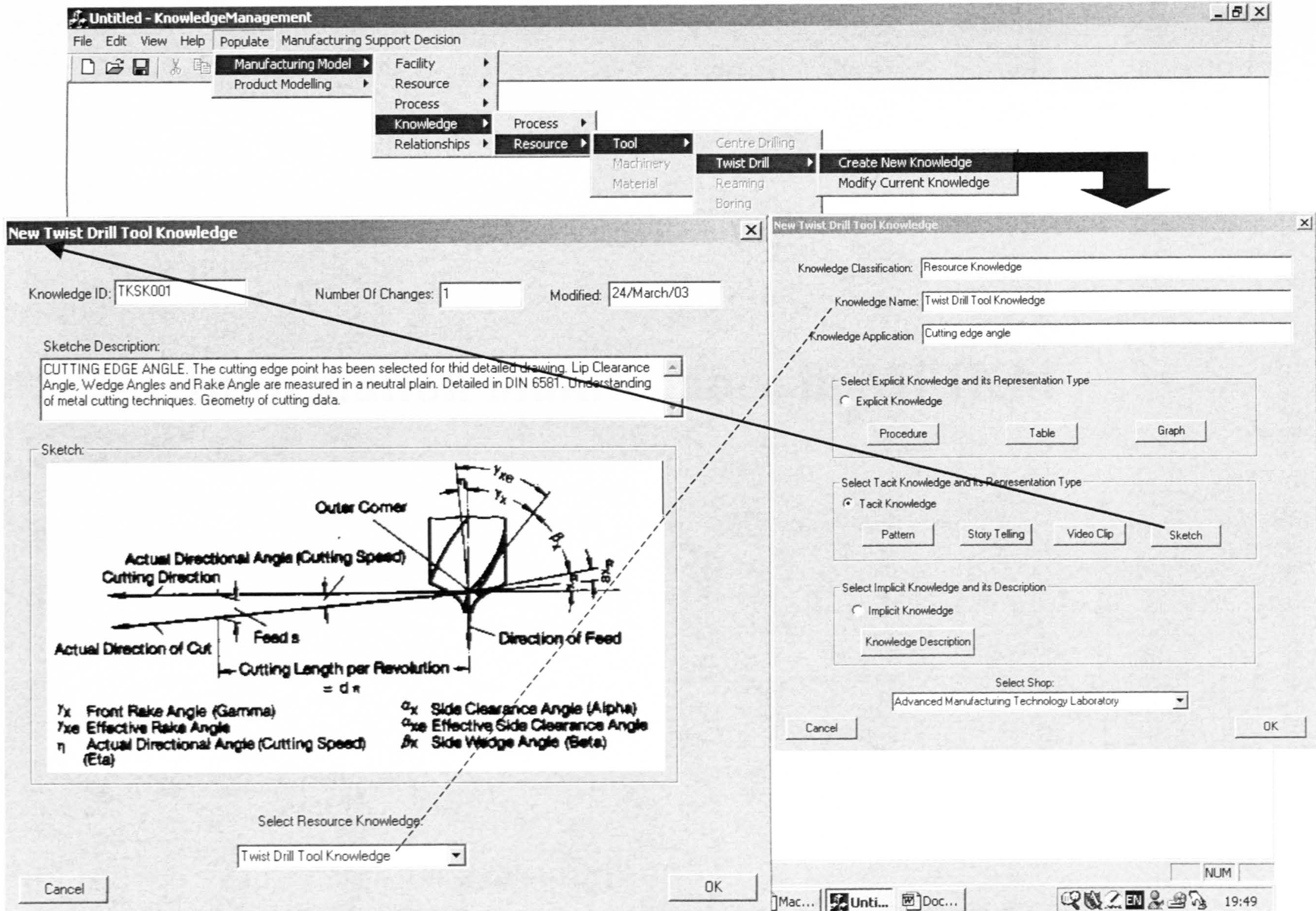


Figure D-4 Tool knowledge population into MFIKM

D-3. Information maintenance in MFIKM

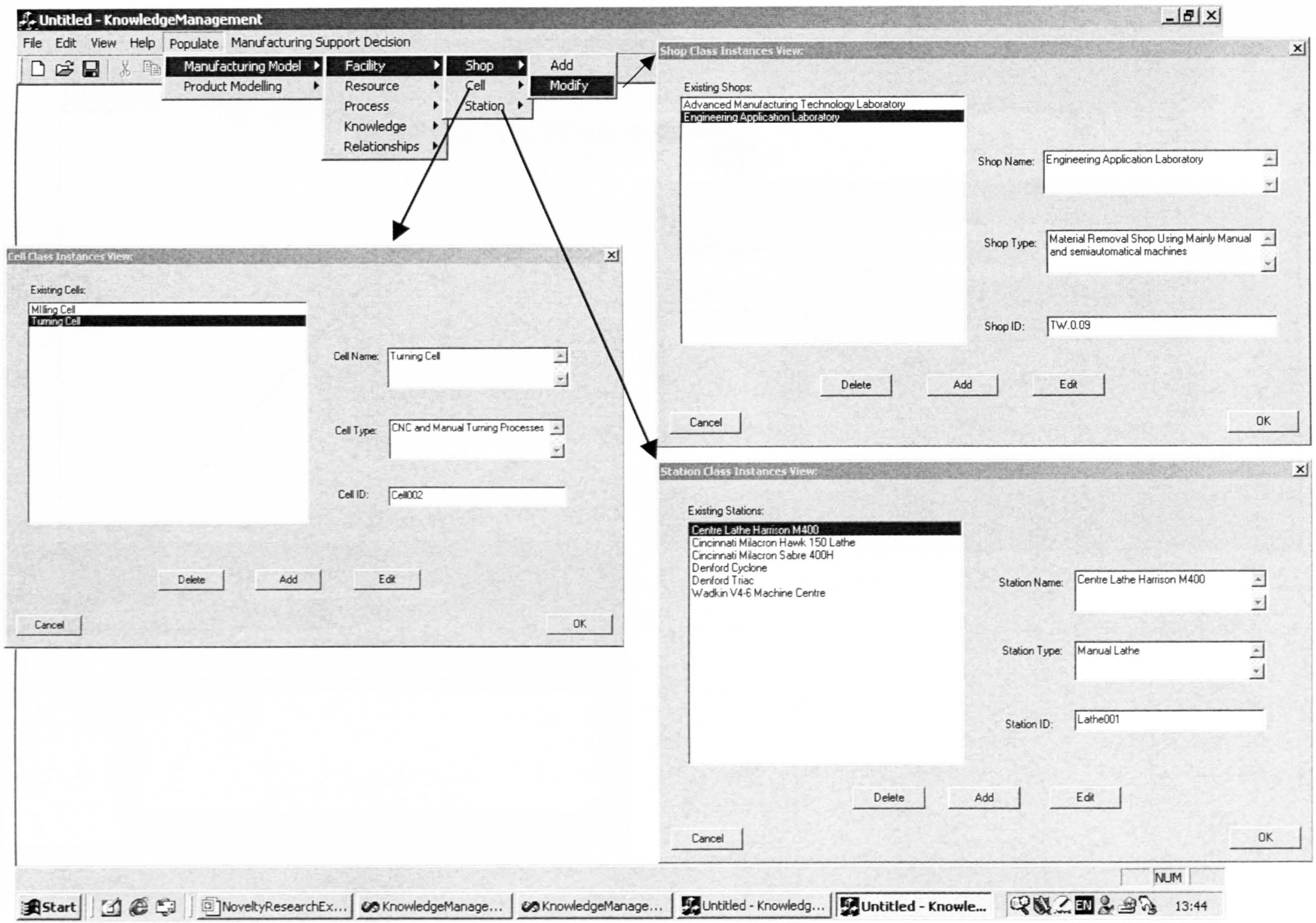


Figure D-5 Maintenance of facility instances information in MFIKM

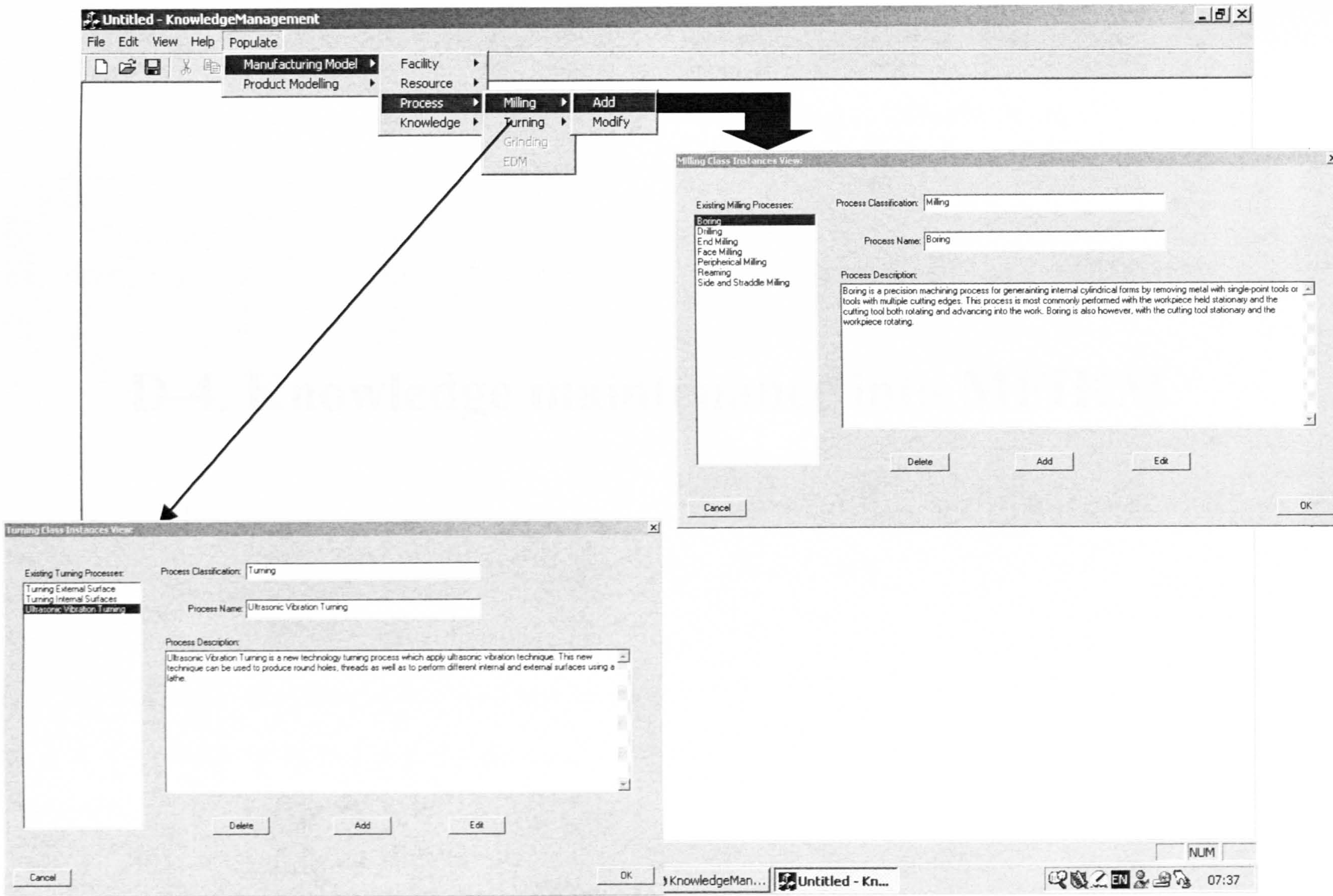


Figure D-6 Maintenance of process instances information in MFIKM (new turning technology process)

D-4. Knowledge maintenance into MFIKM

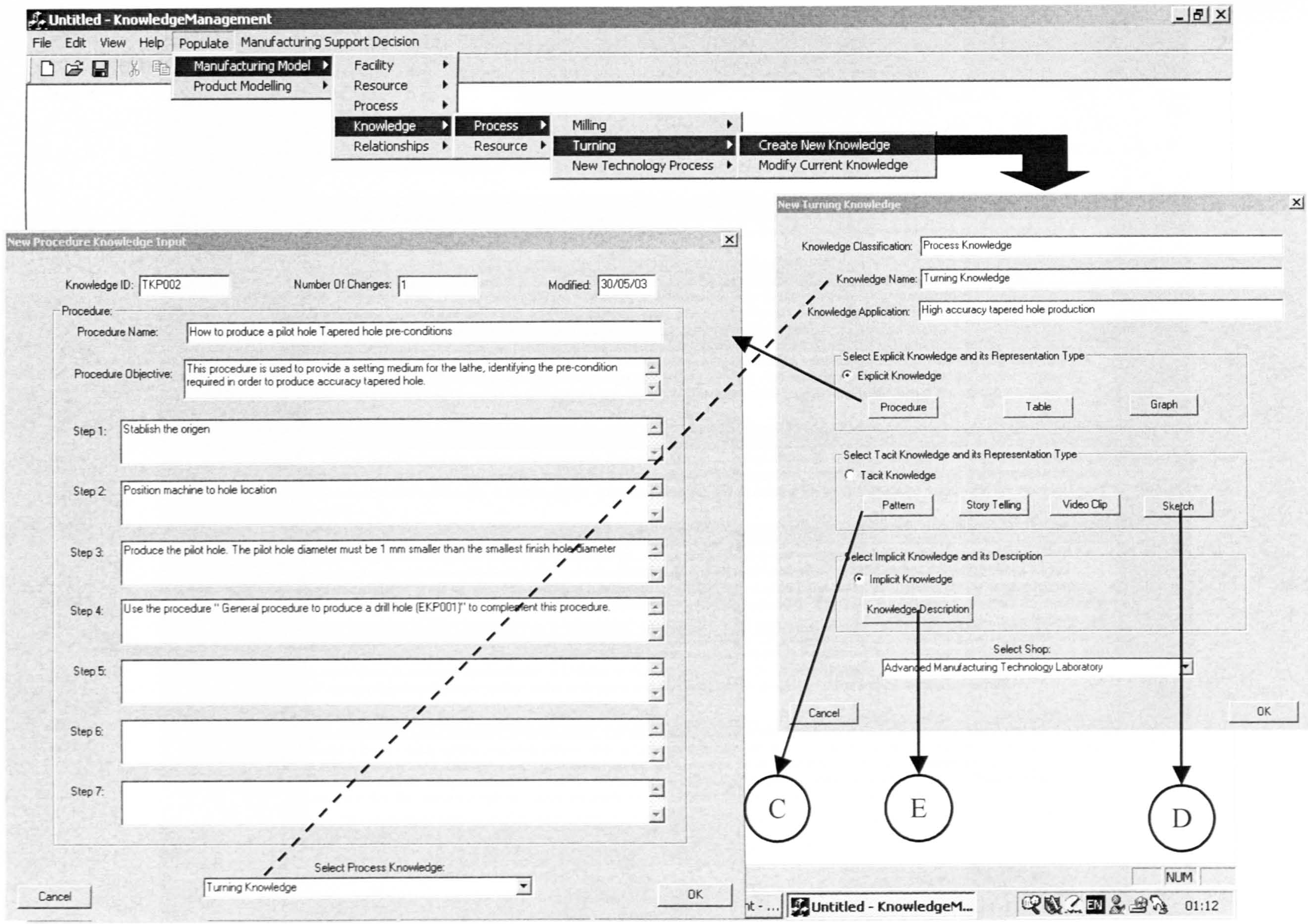


Figure D- 7 New turning knowledge population into MFIKM

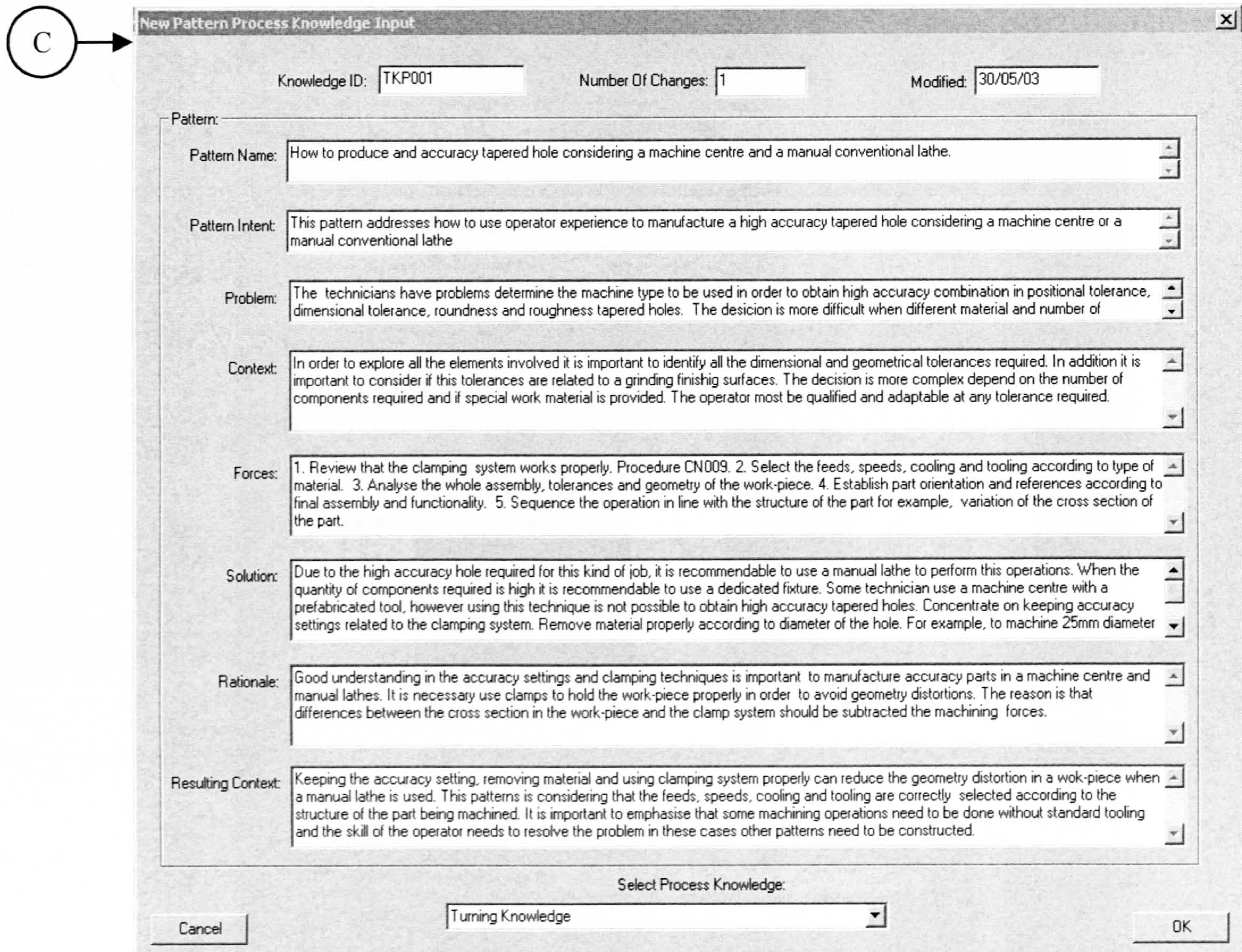


Figure D-8 New turning knowledge population into MFIKM (Cont.)

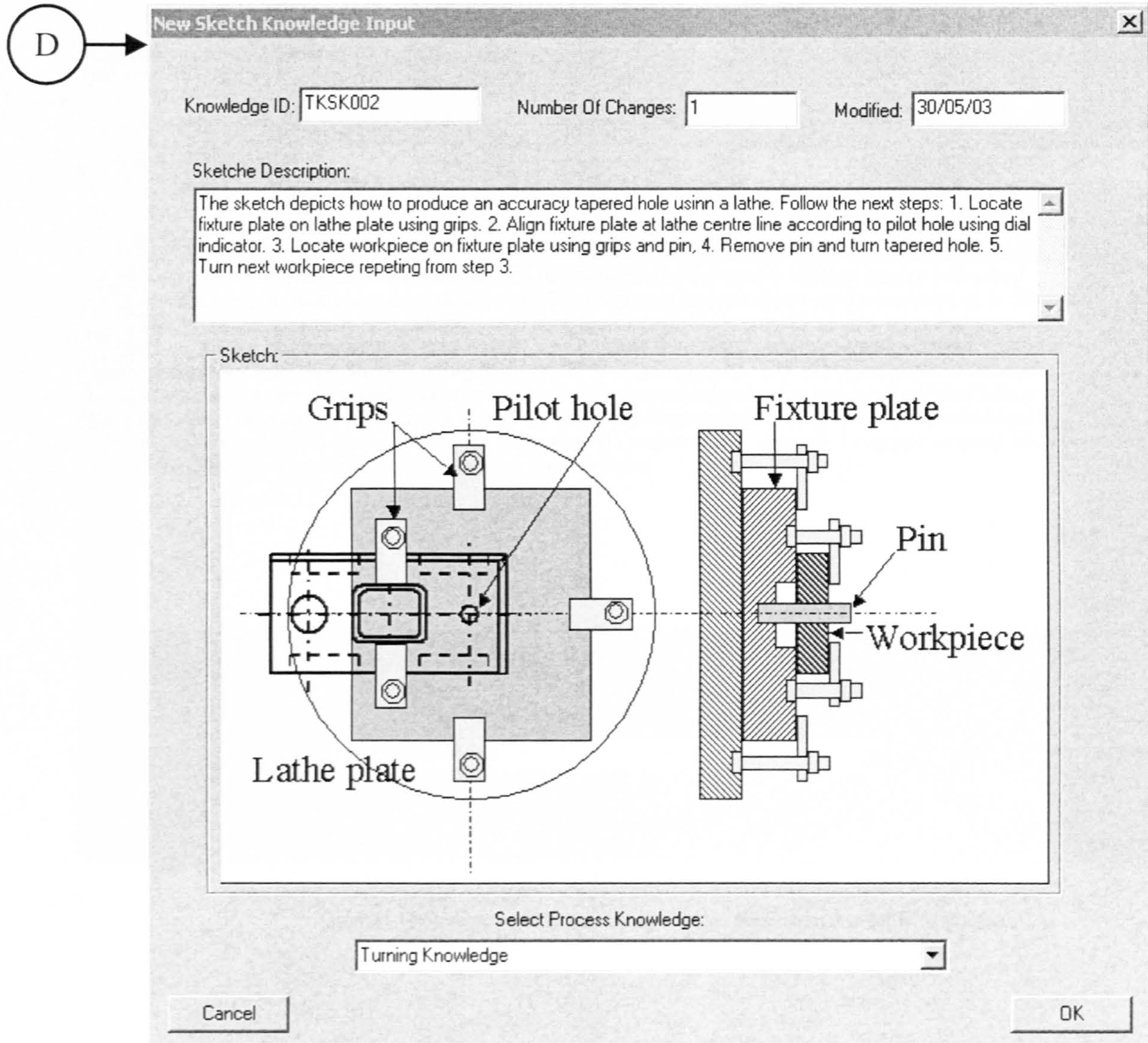


Figure D-9 New turning knowledge population into MFIKM (Cont.)

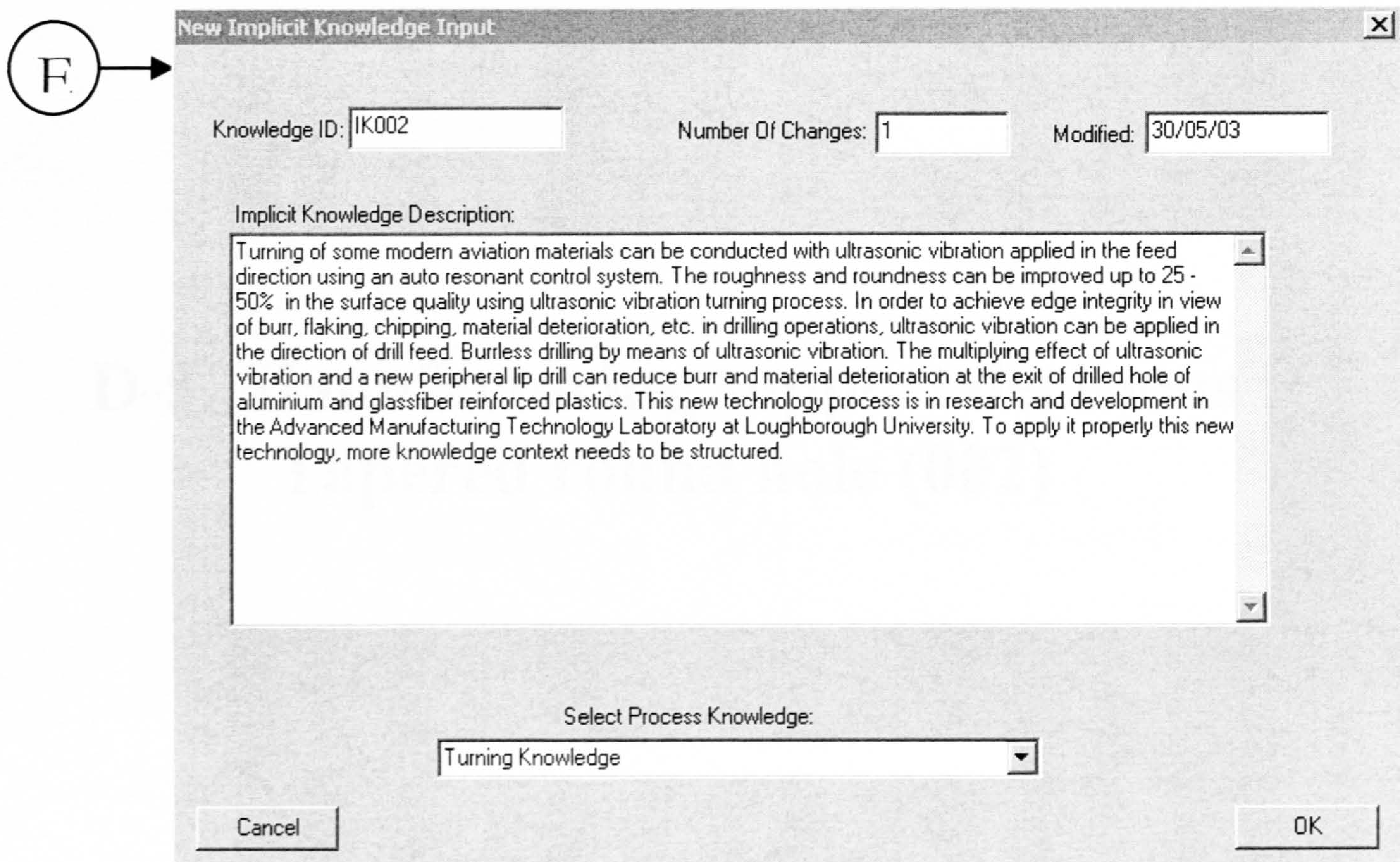


Figure D-10 New technology turning knowledge population into MFIKM (Cont.)

D-5. Manufacturing support decisions
Tapered round hole (002)

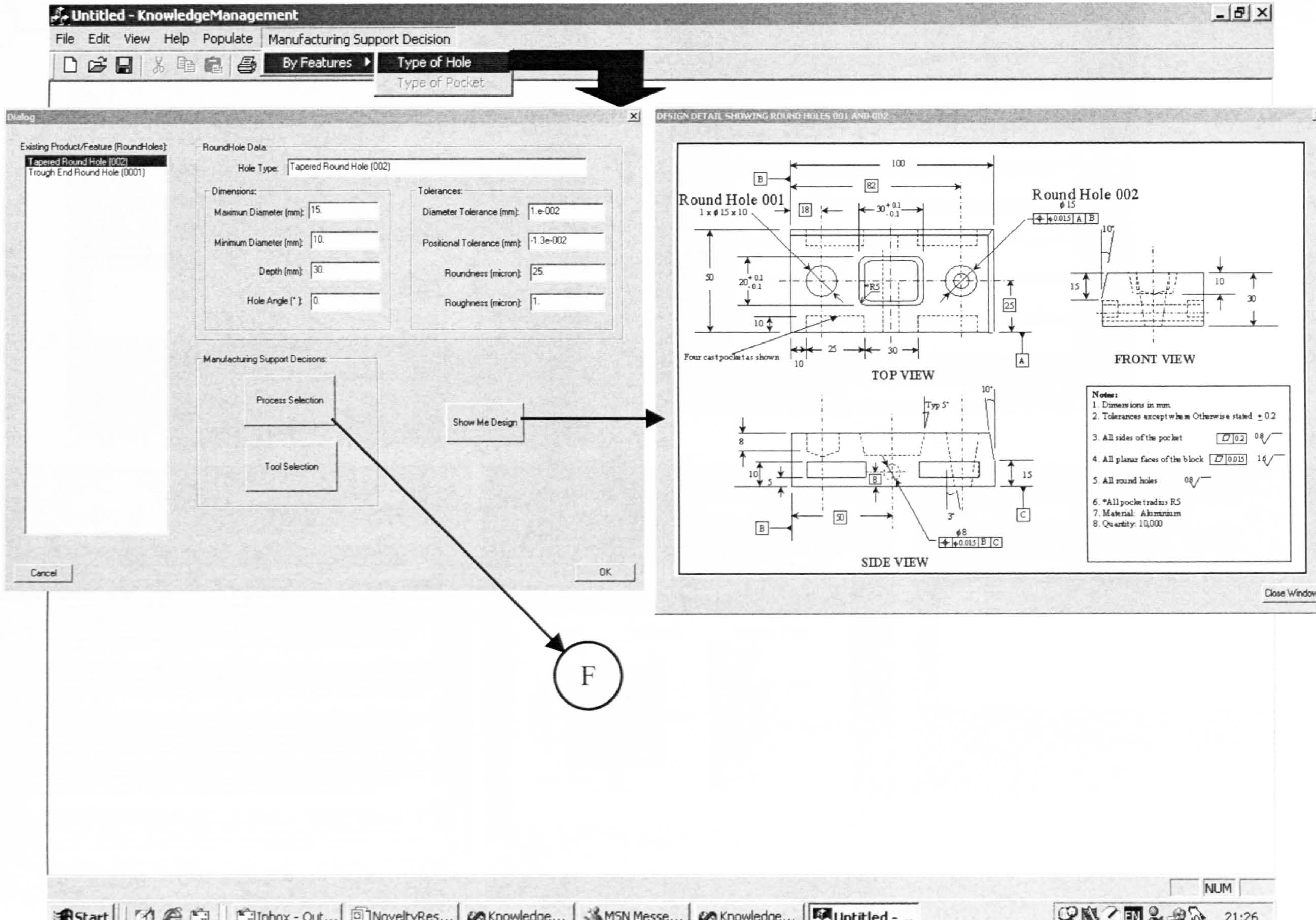


Figure D-11 Manufacturing support decisions (Tapered round hole selection)

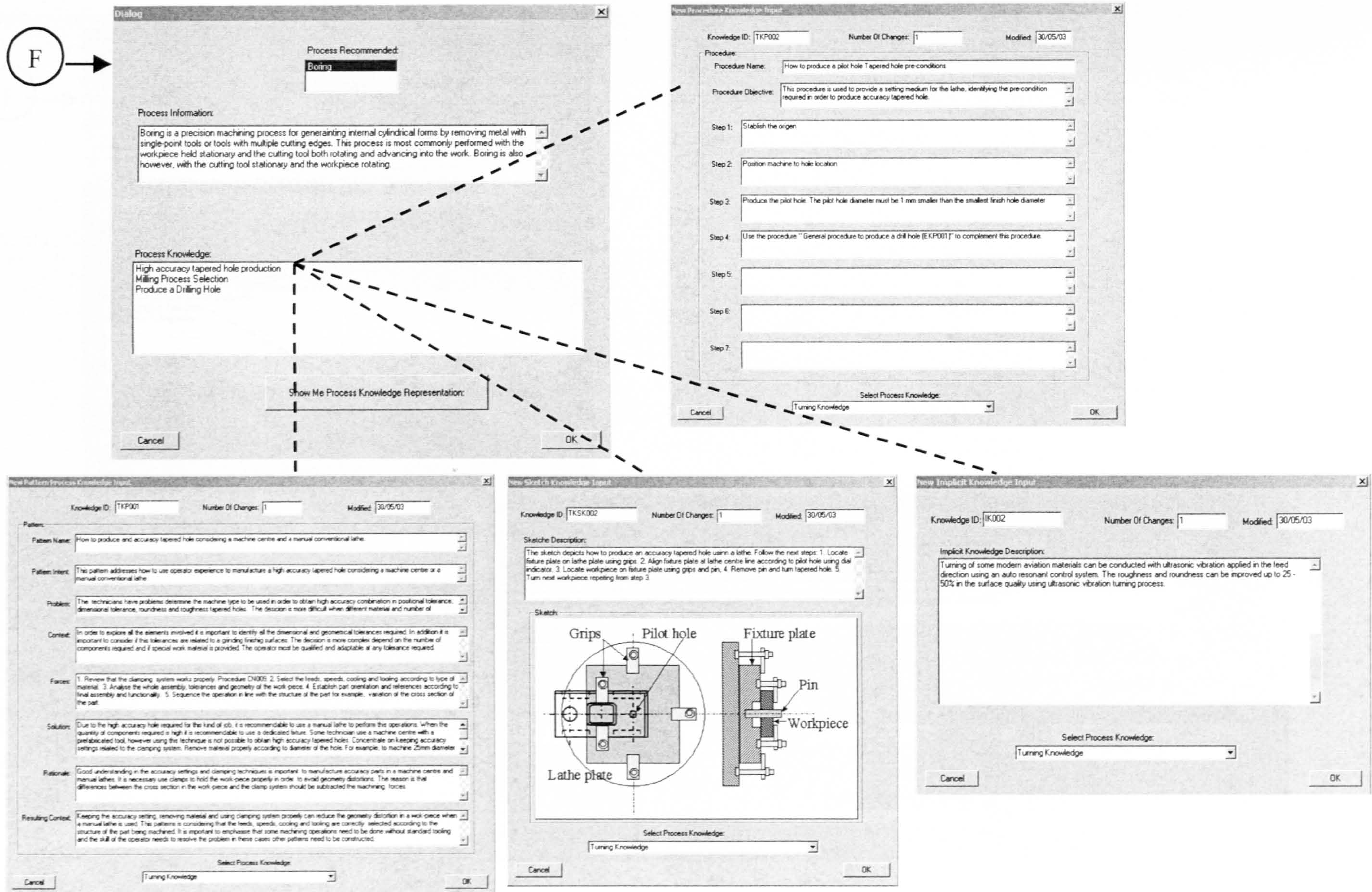


Figure D-12 Manufacturing support decisions cont. (Information and knowledge support)

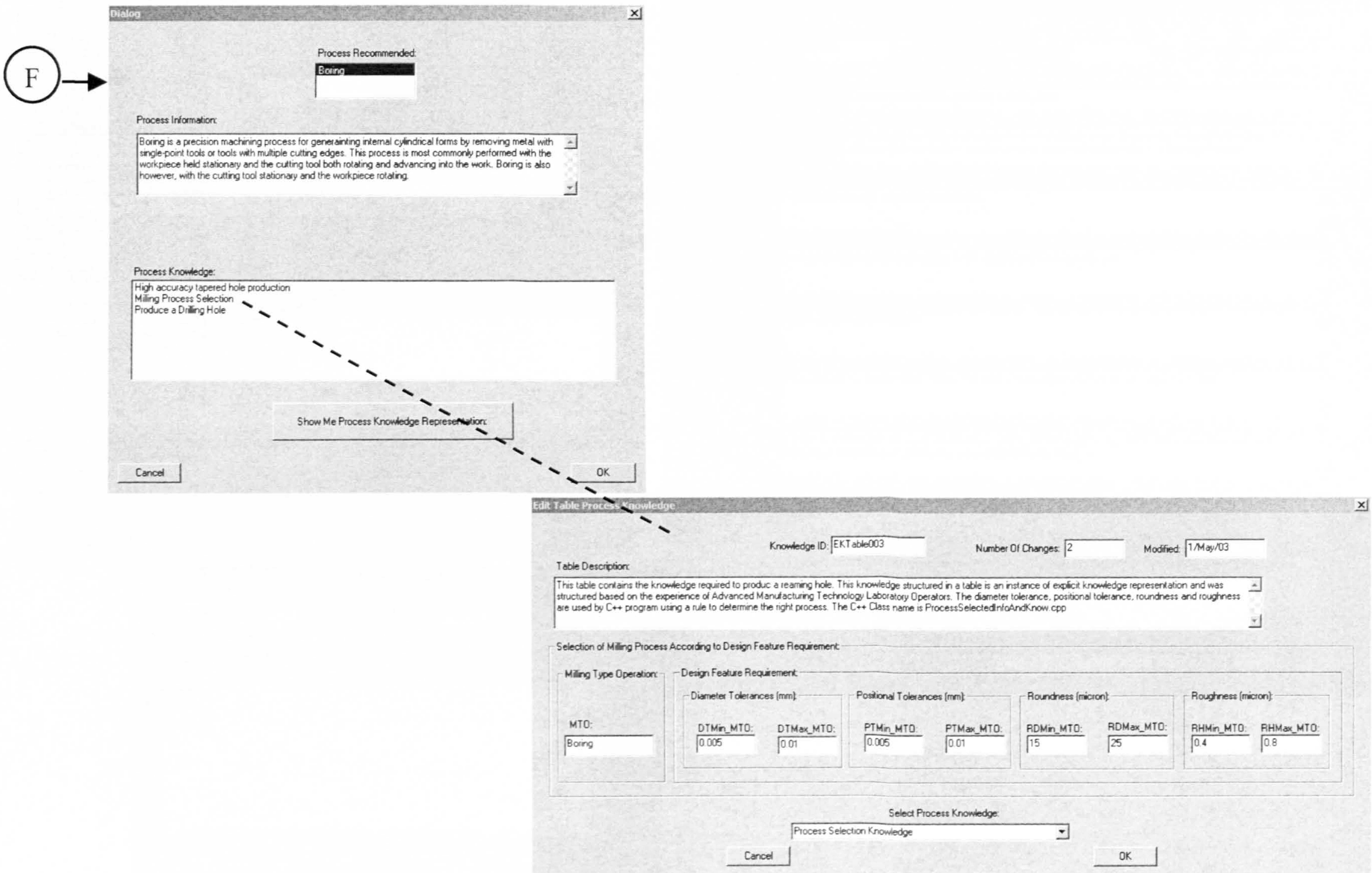


Figure D-13 Manufacturing support decisions (cont.)
Shared knowledge between turning knowledge and process selection knowledge classes

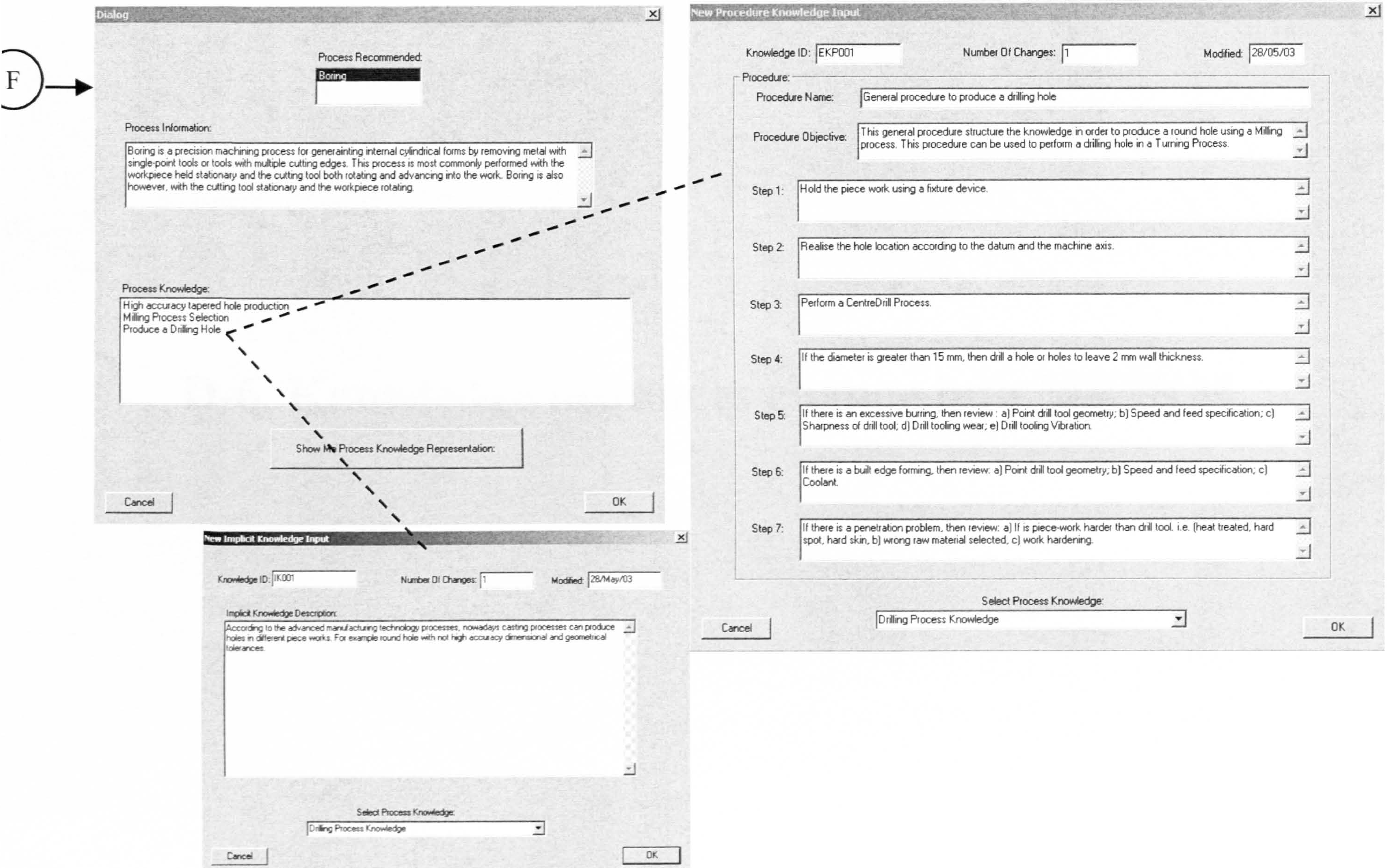


Figure D-14 Manufacturing support decisions (cont.)
Shared knowledge between turning knowledge and milling knowledge classes

D-6. Knowledge instances change into MKIKM

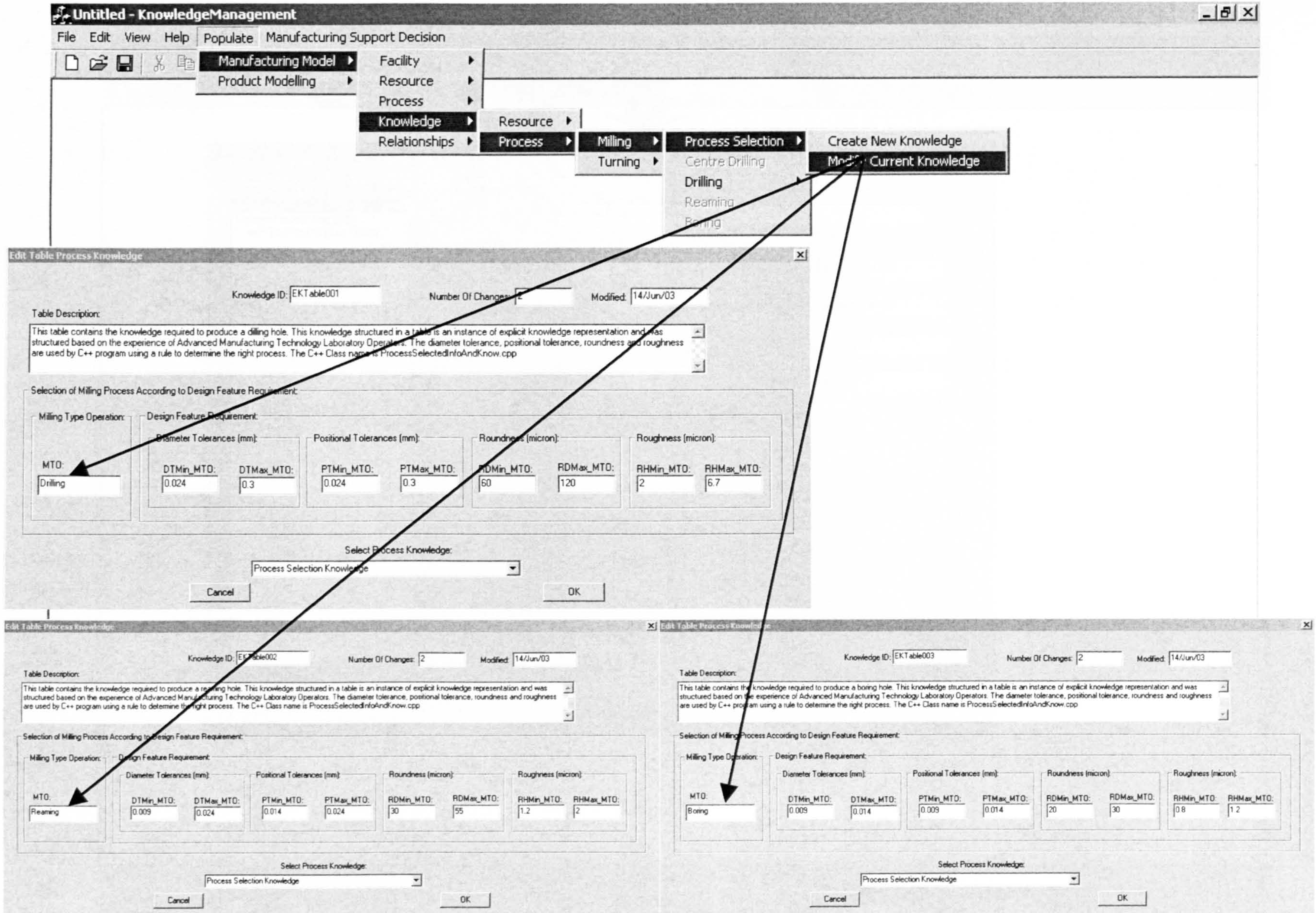


Figure D-15 Process selection knowledge according to manual machines

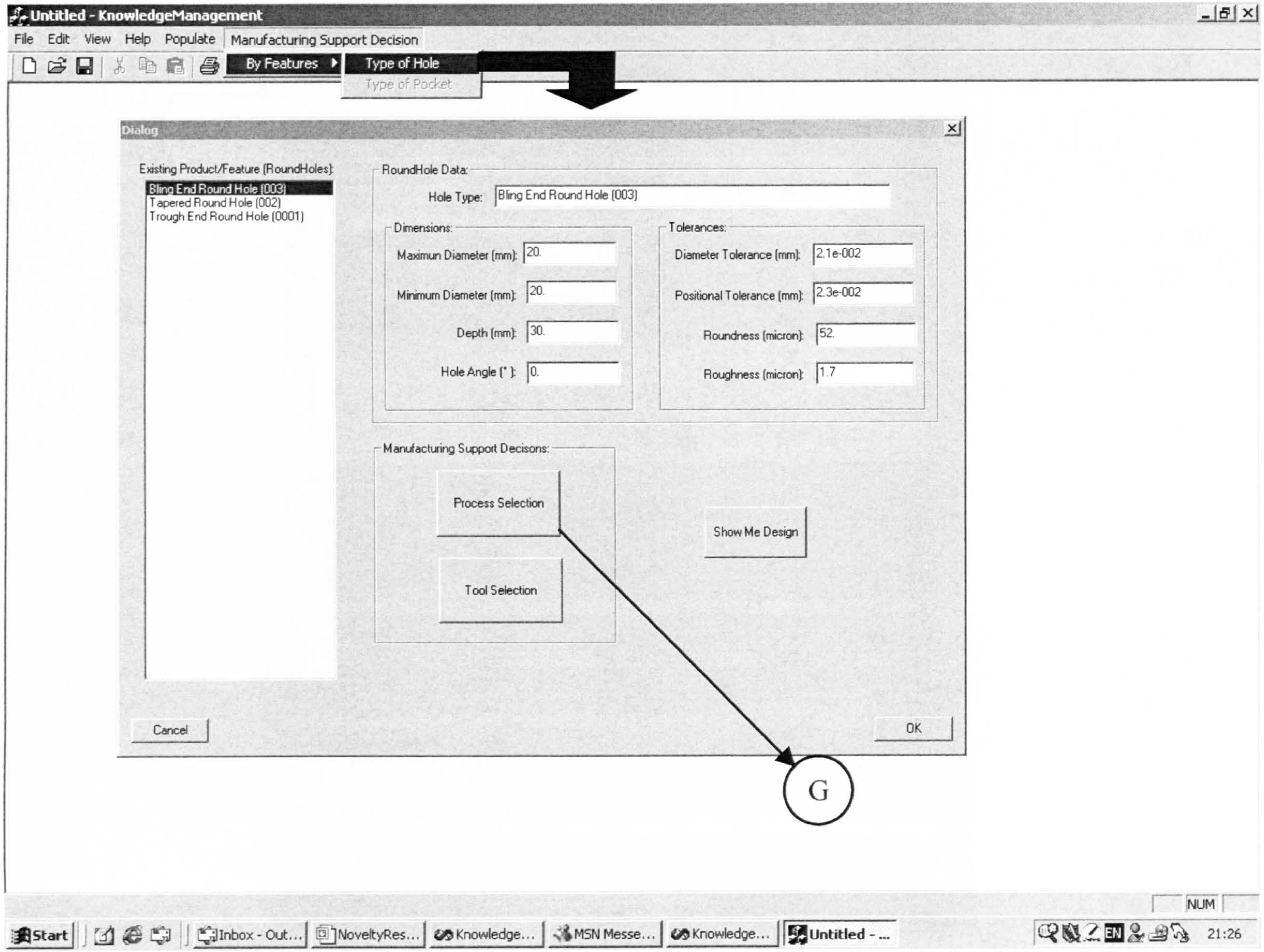


Figure D-16 Manufacturing support decisions (blind end round hole)

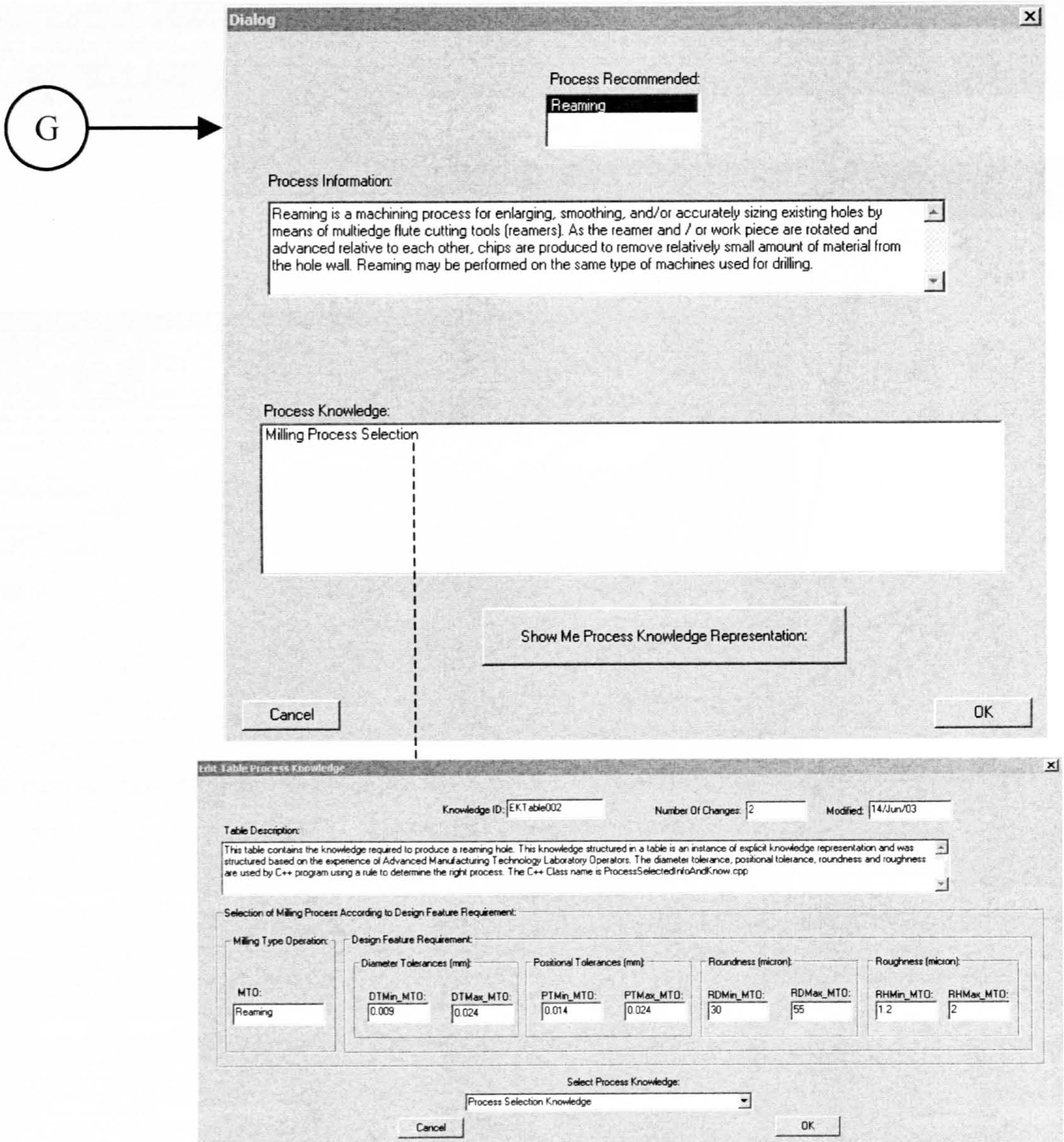


Figure D-17 Manufacturing support decisions (Cont.)

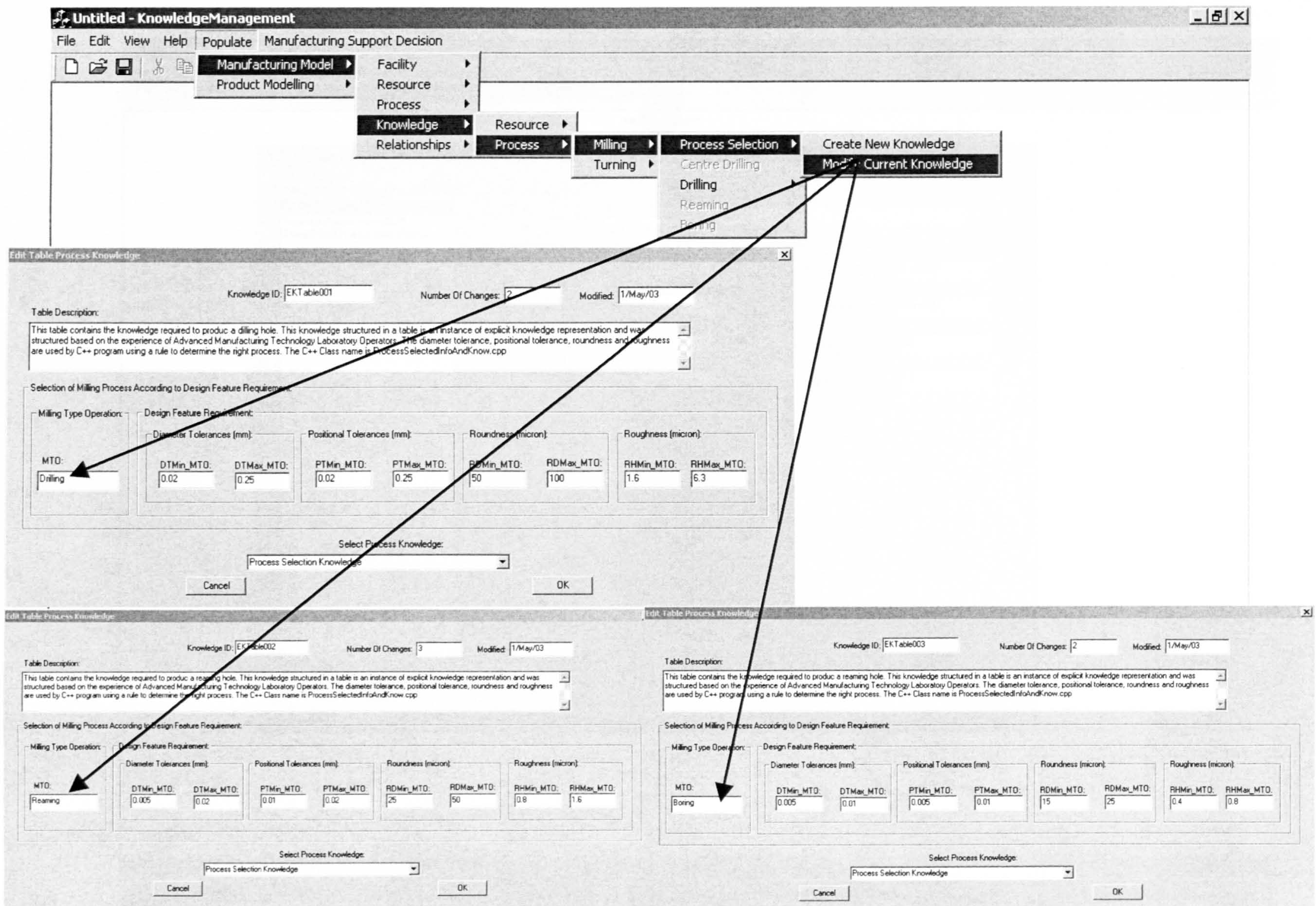


Figure D-18 Process selection knowledge according to CNC machines

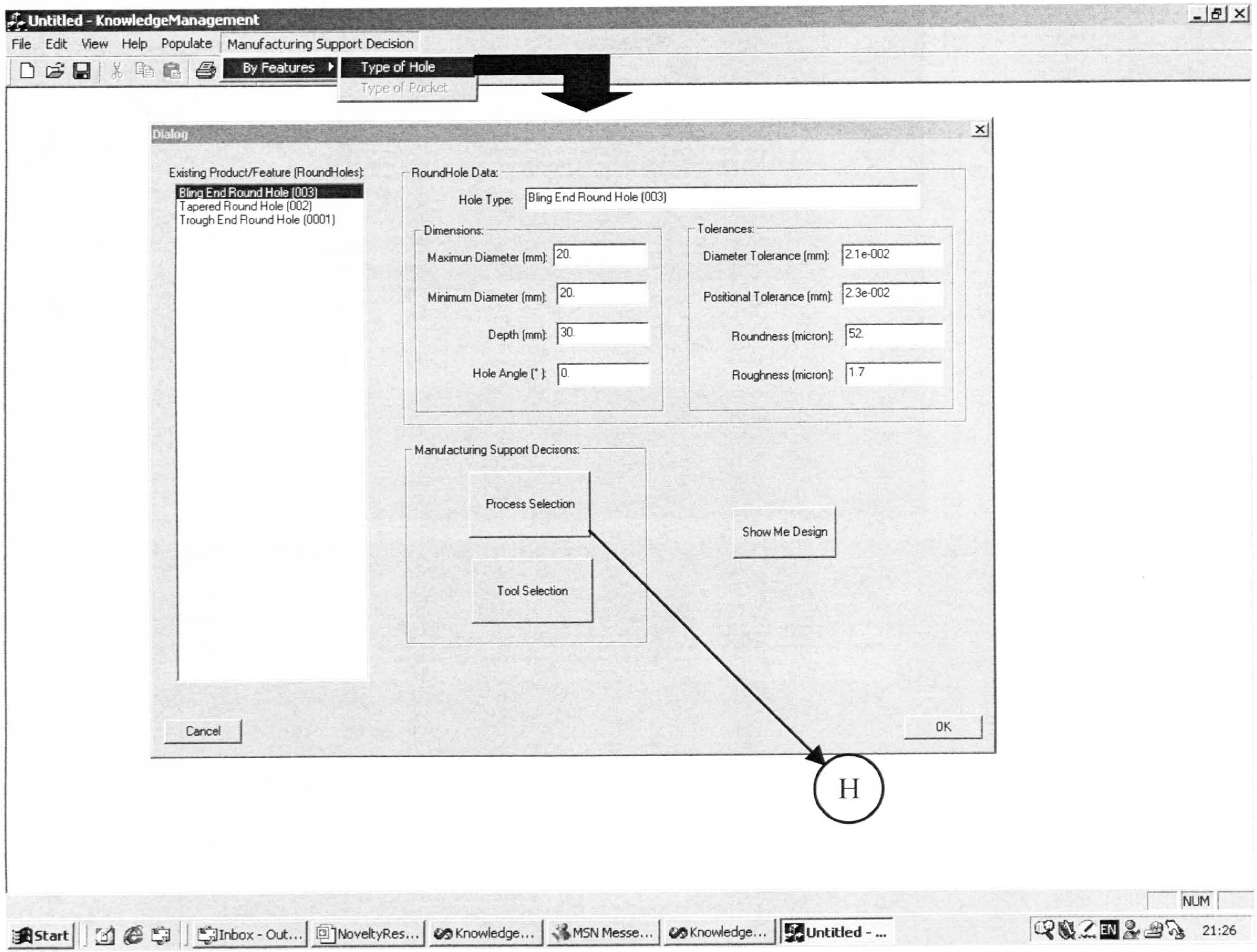


Figure D-19 Manufacturing support decisions (blind end round hole)

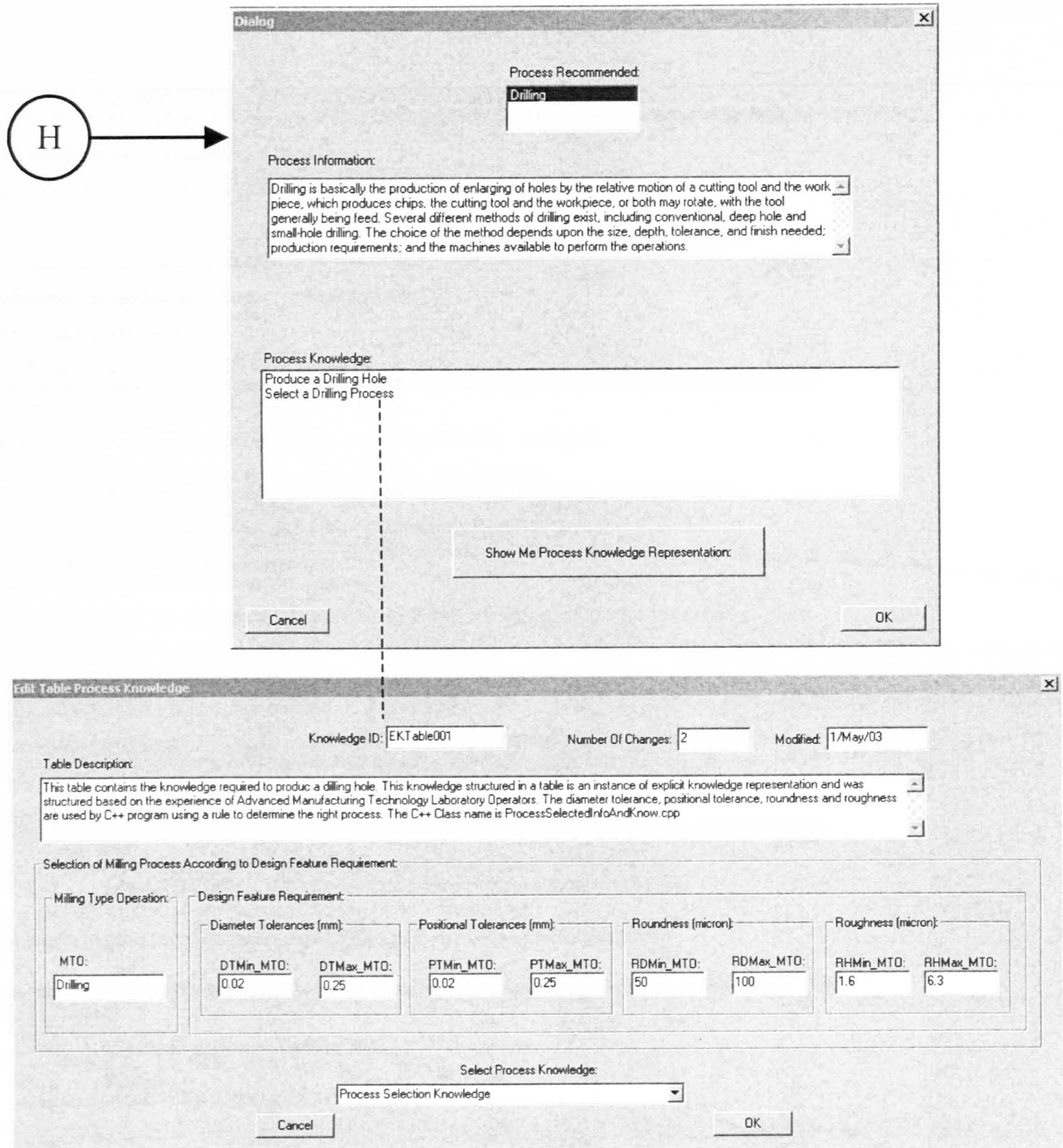


Figure D-20 Manufacturing support decisions (Cont.)

```
// GGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGG
void CProcessSelectedInfoAndKnow::getOsCollection(os_Collection<Process*>*Processcollection)
{
    AllProcessDialog = Processcollection;
}
// GGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGG


/////////////////////////////////////////////////////////////////////////////
// CProcessSelectedInfoAndKnow message handlers

BOOL CProcessSelectedInfoAndKnow::OnInitDialog()
{
    CDialog::OnInitDialog();

    // TODO: Add extra initialization here
// @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
// Initialise the pointer to ListBox

    OS_BEGIN_TXN(ShowProcessSelected,0, os_transaction::update)
    {
        int List_Index_to_Pointer; // Index of the ListBox
        pTableListBox = (CListBox*)GetDlgItem(IDC_LIST_PROCESS_RECOMMENDED);
        pTableListBox->ResetContent();
        os_Cursor<Table*> Cursor_Pointer (*AllTableDialog);
        for (Table* c1=(Table*)Cursor_Pointer.first();
        (Table*) Cursor_Pointer.more();
        c1= (Table*) Cursor_Pointer.next())

// Computational Rule in order to select a milling process using HoleFeature Class
// and Table Class.
if    ((c1->_DTMin_MTO<=pSelHoleFeature->_diameterTolerance)  &&(c1->_DTMax_MTO>=pSelHoleFeature->_diameterTolerance)&&
       (c1->_PTMin_MTO<=pSelHoleFeature->_positionalTolerance)&&(c1->_PTMax_MTO>=pSelHoleFeature->_positionalTolerance)&&
       (c1->_RDMin_MTO<=pSelHoleFeature->_roundnes)           &&(c1->_RDMax_MTO>=pSelHoleFeature->_roundnes)&&
       (c1->_RHMin_MTO<=pSelHoleFeature->_roughness)          &&(c1->_RHMax_MTO>=pSelHoleFeature->_roughness))
        {
            List_Index_to_Pointer = pTableListBox ->AddString(ConvertCharToString (c1->_MTO));
            pTableListBox ->SetItemDataPtr(List_Index_to_Pointer,c1);
        }
    }
    OS_END_TXN(ShowProcessSelected)
// @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

    return TRUE;  // return TRUE unless you set the focus to a control
                  // EXCEPTION: OCX Property Pages should return FALSE
}

void CProcessSelectedInfoAndKnow::OnSelchangeListProcessRecommended()
{

// @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
    int List_Index;
    int Match=0;
    List_Index = pTableListBox-> GetCurSel();
    if (List_Index == LB_ERR) {return;}
    pSelTable = (Table*)
    pTableListBox->GetItemDataPtr(List_Index);
```

Figure D-21 Consequence of knowledge programming change