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# A STEP-NC Compliant CAx System

For Wire-Cutting EDM Component Manufacturing

By

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# ABSTRACT

For the past 20 years, CNC manufacturing has been relying on the proprietary format of G & M codes to control the machining process despite the remarkable advances made in machining and control technologies. This low-level format is based on the vendor-specific ISO 6983 standard, which provides limited information to the CNC producing a primitive machining process language concentrating mainly on the cutting toolpath. Moreover, the ISO 6983 data interface offers little or no interoperability between the different CAD/CAM systems and CNC's, which is recognised as the key shortcoming of the current NC part programming process.

In recent years, a great deal of research effort has concentrated on the development of a new data model for the next generation of CNC's entitled ISO 14649 (STEP-NC). It has been strongly argued that STEP-NC has huge implications on the integration of CAD/CAPP/CAM (CAx) systems, giving the opportunity to realise interoperable CAD to CNC manufacturing. This is largely due to the STEP-NC data model offering a bi-directional data interface with a high-level description of both geometrical and manufacturing information, thus providing a revolution over the current state-of-the-art in CNC manufacturing.

This research provides an investigation into the programming of wire-cutting electrical discharge machining (WEDM) machines using a high level process planning description based on the evolving STEP-NC standard. At present, part 13 of the standard has been dedicated to the non-conventional material removal process employing the use of a specialised thermal machining technique to machine parts with intricate shapes and of varying hardness. The major contribution of this research is the design of a STEP-NC compliant CAx system framework with product and manufacturing information models supporting the WEDM process chain from product design through to machining process planning and CNC manufacturing.

The research shows that conventional NC part programming is CAD-centric and can only offer an interim solution of satisfying the need for the WEDM CNC machining applications. STEP-NC strives for total integration of CAx systems with CNC by focusing on the standardisation of the product and manufacturing information for WEDM CNC manufacturing through the application of ISO 10303 standard (STEP). The research builds on such benefits and potentials of exploring STEP-NC to provide the basis for making a major step forward in facilitating interoperable CNC manufacturing for the WEDM process.



# ABBREVIATIONS

AI	Artificial intelligence
AIM	Application interpreted model
AP	Application protocols
API	Application programming interface
APT	Automatically programmed tool
ARM	Application reference model
ASCII	American standard code for information interchange
B-Rep	Boundary representation
CAD	Computer aided design
CAD*I	CAD Interfaces
CAM	Computer aided manufacturing
CAPP	Computer aided process planning
CAX	CAD/CAPP/CAM
CD	Committee draft
CNC	Computer numerical control
CR	Cutting rate
CSG	constructive solid geometry
DBMS	Database management systems
DIS	Draft international standard
DOE	Design of experiments
EDM	Electrical discharge machining
EIG	School of engineers de Genève at University of Geneva
EPFL	Federal Institute of Technology in Lausanne
ESPRIT	European strategies programme for research into information technology
FAPT	Fanuc Automatically Programmed Tools
FDIS	Final draft international standard
G, D & T	Geometries, dimensions and tolerances
GDLS	General Dynamics Land Systems
HMP	Hybrid machining process
HSTR	High strength and temperature resistive
IGES	Initial graphics exchange specification

<b>ICAM</b>	<b>Integrated CAM</b>
<b>IMS</b>	<b>Intelligent Manufacturing System</b>
<b>IR</b>	<b>Integrated resource</b>
<b>IS</b>	<b>International standard</b>
<b>ISO</b>	<b>International Organisation for Standardisation</b>
<b>JVM</b>	<b>Java virtual machine</b>
<b>MDM</b>	<b>Manufacturing data model</b>
<b>MDSI</b>	<b>Manufacturing Data System, Inc.</b>
<b>MModel</b>	<b>Manufacturing model</b>
<b>MMC</b>	<b>Metal matrix composites</b>
<b>MMR</b>	<b>Material removal rate</b>
<b>NC</b>	<b>Numerical control</b>
<b>NRL-SNT</b>	<b>National Research Laboratory for STEP-NC Technology</b>
<b>OLE</b>	<b>Object linking and embedding</b>
<b>OMAC</b>	<b>Open modular architecture controller</b>
<b>OODBMS</b>	<b>Object-oriented DBMS</b>
<b>OSI</b>	<b>Open systems interconnection</b>
<b>PC</b>	<b>Personal computer</b>
<b>PDDI</b>	<b>Product definition data interface</b>
<b>PDES</b>	<b>Product data exchange specification</b>
<b>PDM</b>	<b>Product data model</b>
<b>PEPS</b>	<b>Production Engineering Productivity System</b>
<b>PModel</b>	<b>Product model</b>
<b>PRF</b>	<b>Proof of a new international standard</b>
<b>SDAI</b>	<b>Standard data access interface</b>
<b>SDK</b>	<b>Software development kit</b>
<b>SET</b>	<b>Standard d'Echange et de Transfert</b>
<b>SF</b>	<b>Surface finish</b>
<b>SFP</b>	<b>Shopfloor-oriented NC programming</b>
<b>STEP</b>	<b>Standard for the transfer and exchange of product model data</b>
<b>N/S</b>	<b>Noise-to-signal</b>
<b>TC184/SC1</b>	<b>Technical committee 184/Subcommittee 1</b>
<b>TC184/SC4</b>	<b>Technical committee 184/Subcommittee 4</b>
<b>TS</b>	<b>Technical specification</b>

UML	Unified modelling language
VAD-FS	Verband Der Automobilindustrie Flachen Schnittstelle
WECG	Wire electrochemical grinding
WEDG	Wire electrical discharge grinding
WEDM	Wire-cutting electrical discharge machining
Wire SNIPs	STEP-NC interoperable process planning prototype system for WEDM
XML	Extensible markup language



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# Chapter 1

## INTRODUCTION

Since the inception of numerical control technology in the early 1950s, low-level G codes (preparatory commands) and M codes (miscellaneous command) have been used to specify the motion of NC machines. Despite significant advancement made in machine development and control technology in the last 35 years resulting in the evolution of the original NC processes, such as milling, into the thermal machining process, such as WEDM, the approach to NC part programming remains relatively unchanged. The very same G & M codes are still in use today to program these state-of-the-art machining processes and impose the CNC with simple cutting motions. These codes define and control the cutting toolpath, which requires to be calculated in terms of position and feedrate. The WEDM process relies on these G & M codes to thermally degrade the component material through the application of a series of discrete electrical discharges occurring between the wire tool and the part. However, the proprietary format of the G & M codes has been the bottleneck in integrating the wide range of CAD/CAM systems used in the generation of part programs for CNC WEDM component manufacturing.

WEDM is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles. It is considered as a unique adaptation of the conventional EDM process, which uses an electrode to initialise the sparking process. However, WEDM utilises a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05-0.3mm. The thinner wire is commonly used to achieve sharp or small radii corners. The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. During the machining process, the material is eroded ahead of the wire and there is no direct contact between the workpiece and the wire, eliminating the mechanical stresses during machining. However, the machining process may require several cuts to produce the desired shape of the part. It includes the roughing cut to remove the slug and the finishing cut to get the required dimension accuracy and surface finish quality. This is mainly due to the large amount of wear occurring on the wire during the roughing cut, thereby producing a very coarse surface finish on the machined part. WEDM process is able to machine exotic and high strength and temperature resistive (HSTR)



materials and eliminate the geometrical changes occurring in the machining of heat-treated steels.

In many CNC manufacturing environments, CAD/CAM systems are used to define the component design and machining operation processes. The CNC programmer defines the part design by using a CAD system and determines the machining operation through the use of a CAM system. The end result is a cutting toolpath written in cutter location data format, which is subsequently imported to the post-processor generating the NC part program for a vendor-specific machine controller. However, the NC part program is scrutinised with G & M codes entailing simple 'go to point' instructions, which no longer satisfy the functional requirements of the modern-day CNC manufacturing. Furthermore, the CNC has the exclusive use of G & M codes, which isolate the CNC from the other CAD/CAM functions, in terms of information sharing and exchange. Such constraints are at the basis of a need to explore a high-level process planning description and interface, which can integrate the CAD to CNC process chain.

A new data model, informally known as STEP-NC, has been developed to revolutionise the current approach of CAD/CAM programming for CNC WEDM component manufacturing. It is primarily based on the ISO 14649 standard (2003) to provide a bi-directional data interface between different CAX systems and a new breed of intelligent CNC. Current part programming practice uses vendor-specific interpreted G & M codes based on the ISO 6983 standard (1982), otherwise known as RS 274D (1979), to program a CNC WEDM machine. It produces ad-hoc information content and data format, which cannot adequately satisfy the different system functional needs of sharing and exchanging information between the systems. STEP-NC aims to solve these problems through the use of the STEP (Standard for the Transfer and Exchange of Product model data) neutral product data transfer format ISO 10303 (1994) of representing both the design and manufacturing intent. The neutral format ensures that the information would not change throughout the product life cycle or with the ever-advancing computing technology. In addition, STEP-NC seeks to capture the complete information requirements to support the operation and the control of the various CNC WEDM activities.

The integrity of standardised repositories of product and manufacturing information is crucial to the planning, operating and controlling of the WEDM process. STEP-NC's data model



seeks to specify the information about the manufacturing capability of a process by mapping it onto the design specification of a part, thereby producing a feasible machining process plan for the part. In order to facilitate the evaluation of the impact of the product design on the manufacturing process at the early stage of product development, the two information repositories are closely integrated. The result of integrating the information repositories also helps to promote interoperable manufacturing of parts at different locations/companies. These benefits are largely made possible through the sharing and exchanging of product and process knowledge among different design and manufacturing software systems, thus facilitating integrated and interoperable product design, process planning and machining.

A widely accepted method of integrating the different sources of information to support machining process planning is through information modelling. It ensures the effective representation of both the product and process knowledge, which require to be seamlessly integrated in the CNC manufacturing environment. The aim of this research is to provide an investigation into the programming of WEDM machines using a high level process planning description based on the ISO 14649 standard. This is mainly carried out by identifying the generic information models needed to support CNC manufacturing decision-making through the integration of information across the WEDM CAX to CNC process chain. As a result, it enables the information models to provide a consistent information exchange and the interoperability of product design and manufacturing information for WEDM components both from the CAD system to the CNC and CNC to CAD. This research presents a system framework that supports the various part programming and machining process planning activities for WEDM component manufacturing within a STEP-NC compliant manufacturing environment.

The major research questions explored in this thesis are:

- a. that a high-level process planning description based on a new manufacturing standard can be used to describe the geometrical and manufacturing requirements of a WEDM component
- b. that the information models can be used to support the interoperable manufacturing of WEDM components in the CAD to CNC process chain

The thesis is divided into four main sections, which are depicted in figure 1.1 and described as follows:

*i. Background/literature review section*

This section provides the introduction and scope of the research. The latter identifies the aims and objectives of the research, which lead to a number of research areas undertaken by the author. One of the research areas involves the review on the various academic researches into the WEDM process and the advent of STEP-NC for CNC manufacturing, which is also included in this section. The review on the WEDM process gives an overview of the widely accepted non-traditional material removal process, thereby providing an insight into the planning of the WEDM process. On the other hand, the review on the STEP-NC studies its implication on the programming a component for CNC manufacturing through the use a high level process planning description based on the ISO 14649 standard.

*ii. Theoretical research section*

This section identifies a generic system framework and the two fundamental information models supporting an interoperable CAD to CNC manufacturing within a STEP-NC environment for the WEDM process. The system framework is described by exploring the information and functional perspectives of the CAx to CNC process chain. Whereas the information models are described in the context of modelling the product and manufacturing information needed to facilitate the planning of the WEDM process through the use of the ISO 14649 standard.

*iii. Experimental research section*

This section outlines the development and evaluation of a prototype system based on the system framework and the information models identified in the previous section. The computational environment for the prototype system is described in this section in terms of the development, functional and operational structure to generate a STEP-NC process plan for WEDM component manufacturing. The prototype system is subsequently tested through the use of the example case study found in the ISO/DIS 14649-13. It is evaluated not only on the functionality of generating the STEP-NC process plan for the example parts but also on the information needed to adequately carry out the planning of a WEDM process.



iv. *Research conclusion section*

This section discusses and concludes the various research areas surrounding the design and implementation of the STEP-NC compliant CAx system for WEDM component manufacturing. It also includes appendices relating to the testing of the prototype system.

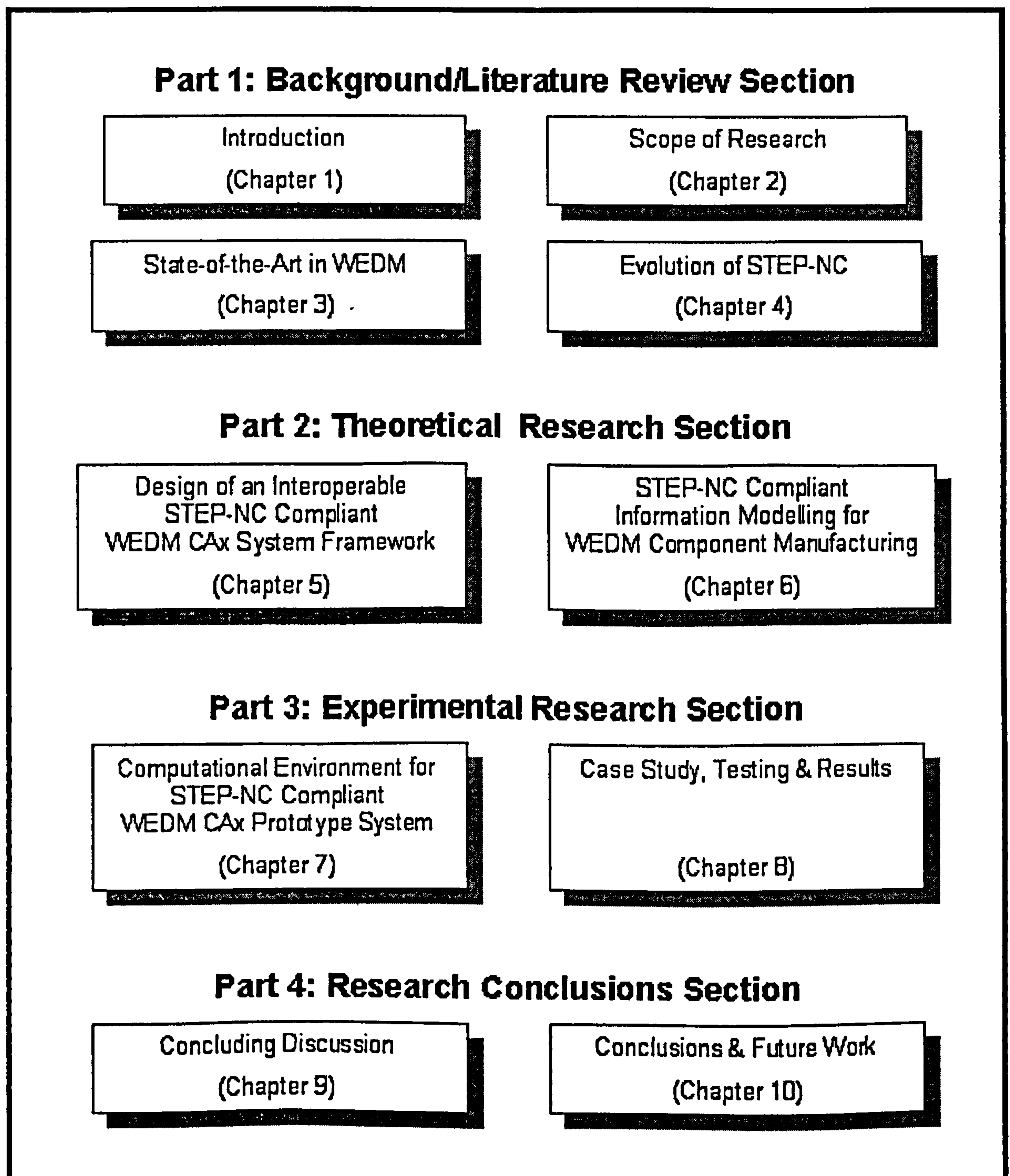


Figure 1.1 The structure of the chapters in the thesis



## **Chapter 2**

### **SCOPE OF RESEARCH**

#### **2.1 Introduction**

This chapter describes the scope of the research reported in the thesis. It identifies the aims and objectives leading to a number of research areas undertaken by the author.

#### **2.2 Research aims and objectives**

The aims of the research are as follows:

- a. To investigate the programming of WEDM CNC machines by using a high level process planning description based on the ISO 14649 standard
- b. To explore the use of process planning information based on the ISO 14649 standard to support the interoperable CAD to CNC manufacturing of WEDM components

The objectives of the research are as follows:

- i. Review the major WEDM research areas including process optimisation, process monitoring and control together with process development and applications
- ii. Review the state-of-the-art NC part programming and the advent of STEP-NC in programming a component for CNC manufacturing
- iii. Design a framework for a WEDM CAX system to support interoperable CAD to CNC manufacturing within a STEP-NC environment
- iv. Identify the STEP-NC compliant information models for capturing the information requirements needed to perform the various WEDM machining process planning activities
- v. Develop a computational prototype system based on the CAX framework and the information models to program a WEDM component for CNC manufacturing
- vi. Evaluate the prototype system by using a case study and comparing it against state-of-the-art CAD/CAM systems

## 2.3 Scope of research

The scope of the research forming the fundamental structure of the thesis is as follows:

### 2.3.1 *State-of-the-art in WEDM*

Over the last 45 years, the WEDM process has remained as a competitive and economical machining alternative. It is capable of machining parts with varying hardness or geometrically complex shapes, which are very difficult to be machined by the traditional chip forming machining processes. This part of the literature research will review the vast array of research work, carried out from the inception to the development of the WEDM process, exploring the different methodologies of achieving the ultimate WEDM goals of optimising the numerous process parameters and improving the overall machining efficiency.

### 2.3.2 *Evolution of STEP-NC*

The interoperability of CNC manufacturing is largely achieved by the neutral data format of representing and exchanging the product and manufacturing information between different design and manufacturing software systems. This research will review the various data transfer efforts of capturing and preserving the complete information requirements to support the operation and the control of the CNC manufacturing activities. The major part of this research will describe the evolution of STEP-NC by reviewing the conventional CNC part programming methods of manufacturing a component.

### 2.3.3 *Design of an interoperable STEP-NC compliant WEDM CAx system framework*

STEP-NC has huge implications on the integration of CAx systems giving the opportunity to realise interoperable CNC manufacturing. This part of the theoretical research will investigate the use of a generic system framework, which exploits product and manufacturing information, to support the decision-making relating to WEDM process planning and the generation of the STEP-NC process plan. The framework is intended to provide a platform for facilitating the interoperable manufacturing of a WEDM component through the seamless integration of product and manufacturing information across the CAx process chain.

### 2.3.4 *STEP-NC compliant information modelling for WEDM component manufacturing*

The feasibility of planning the WEDM process is dependent on the integrity of the standardised repositories of product and manufacturing information. This research will aim to define two fundamental information models, namely the product and manufacturing models,

representing the vital information required to support the various part programming/machining process planning activities for the WEDM process. The models are based on Part 13 of ISO 14649 standard (2003), which is dedicated to the WEDM process, together with Part 10 of the standard (2004), which specifies the general machining information.

### *2.3.5 Computational environment for STEP-NC compliant WEDM CAx prototype system*

The experimental part of the research will involve the development of a STEP-NC compliant WEDM CAx prototype system to demonstrate the viability of the information models, identified in section 2.3.4, in the application domain through the use of a WEDM example part. The system will be based on the framework, identified in section 2.3.3, and will demonstrate the use of information models for STEP-NC compliant WEDM CNC manufacturing. It is constructed on the basis of structuring the information aspect and constructing the functional aspect of the system through the use of the unified modelling language (UML) class diagrams, IDEF0 activity modelling methodology, ObjectStore database management systems (DBMS) and Java programming language.

### *2.3.6 Case study, testing and results*

The STEP-NC compliant WEDM CAx prototype system will be evaluated with a case study based on two example WEDM parts specified in the ISO/DIS 14649-13 standard. It will be tested to gauge the system performance of planning the WEDM process and generating the process plan within a STEP-NC manufacturing environment. The viability of the STEP-NC compliant information models supporting the various WEDM product design and WEDM manufacturing process activities will also be tested. This will involve the comparison between the prototype system and two commercial state-of-the-art WEDM CAD/CAM systems, in terms of the data input/output, programming activities and process planning rules. This should enable the research to be put in perspective of today's CAD to CNC programming systems.



## Chapter 3

# STATE-OF-THE-ART IN WIRE ELECTRICAL DISCHARGE MACHINING

### 3.1 Introduction

This chapter provides a review, which has been published in (Ho *et al.* 2004), on the various academic research areas involving the WEDM process. It is the sister paper to a review by Ho and Newman (2003) on die-sinking EDM. The chapter first presents the machining process overview based on the widely accepted principle of thermal conduction and highlights some of WEDM applications. The main section of the chapter focuses on the major WEDM research activities, which include the machining process optimisation together with the machining process monitoring and control. It gives an outline of the various factors affecting the machining performance and productivity, thereby providing an insight into the planning of the WEDM process, which will be discussed in detail in chapter 5. The final part of the chapter critiques the major research areas and the possible research directions.

### 3.2 WEDM

This section provides the basic principle of the WEDM process and the variations of the process combining other material removal techniques.

#### 3.2.1 History of WEDM

WEDM was first introduced to the manufacturing industry in the late 1960s. The development of the machining process was the result of seeking a technique to replace the machined electrode used in EDM. In 1974, D. H. Dulebohn applied the optical-line follower system to automatically control the shape of the component to be machined by the WEDM process (Jameson 2001). By 1975 its popularity was rapidly increasing, as the process and its capabilities were better understood by the industry (Benedict 1987). It was only towards the end of the 1970s, when CNC system was initiated into WEDM that brought about a major evolution of the machining process. As a result, the broad capabilities of the machining process were extensively exploited for any through-hole machining owing to the wire, which has to pass through the part to be machined. The common applications of WEDM include the



fabrication of the stamping and extrusion tools and dies, fixtures and gauges, prototypes, aircraft and medical parts, and grinding wheel form tools.

### 3.2.2 WEDM process

The material removal mechanism of WEDM is very similar to the conventional EDM process involving the erosion effect produced by the electrical discharges (sparks). In WEDM, material is eroded from the workpiece by a series of discrete sparks occurring between the workpiece and the wire separated by a stream of dielectric fluid, which is continuously fed to the machining zone (Puri and Bhattacharyya 2003), as shown in figure 3.1. However, today's WEDM process is commonly conducted on workpieces that are totally submerged in a tank filled with dielectric fluid. Such a submerged method promotes temperature stabilisation and efficient flushing especially in cases where the workpiece has varying thickness. The WEDM process makes use of electrical energy generating a channel of plasma between the cathode and anode (Shobert 1983), and turns it into thermal energy (Tsai *et al.* 2003) at a temperature in the range of 8,000 to 12,000°C (Boothroyd 1989) or as high as 20,000°C (McGeough 1988) initialising a substantial amount of heating and melting of material on the surface of each pole. When the pulsating direct current power supply occurring between 20,000 to 30,000Hz (Krar 1997) is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten particles from pole surfaces in the form of microscopic debris.

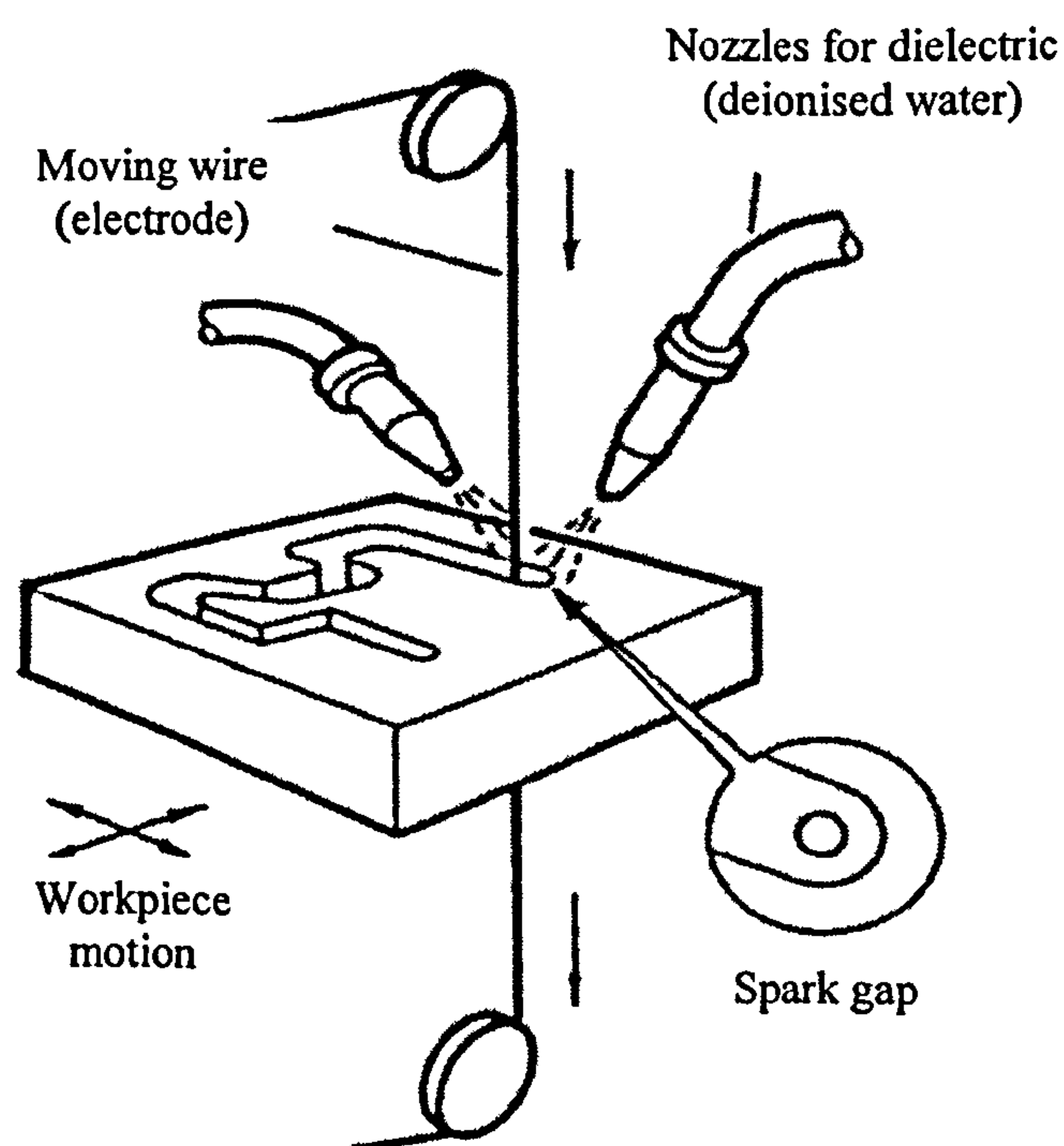


Figure 3.1 Basic elements of the WEDM process (Boothroyd 1989)

While the material removal mechanisms of EDM and WEDM are similar, their functional characteristics are not identical. WEDM uses a thin wire continuously feeding through the workpiece by a microprocessor, which enables parts of complex shapes to be machined with exceptional high accuracy. A varying degree of taper ranging from  $15^\circ$  for a 100mm thick to  $30^\circ$  for a 400mm thick workpiece can also be obtained on the cut surface. The microprocessor also constantly maintains the gap between the wire and the workpiece, which varies from 0.025 to 0.05mm (Benedict 1987). WEDM eliminates the need for elaborate pre-shaped electrodes, which are commonly required in EDM to perform the roughing and finishing operations. In the case of WEDM, the wire has to make several machining passes along the profile to be machined to attain the required dimensional accuracy and surface finish (SF) quality. Kunieda and Furudate (2001) tested the feasibility of conducting dry machining to improve the accuracy of the finishing operations, which was conducted in a gas atmosphere without using dielectric fluid. The typical cutting rates (CRs) are  $300\text{mm}^2/\text{min}$  for a 50mm thick D2 tool steel and  $750\text{mm}^2/\text{min}$  for a 150mm thick aluminium (Kalpajian and Schmid 2003), and SF quality is as fine as  $0.04\text{--}0.25\mu\text{m Ra}$ . In addition, WEDM uses deionised water instead of hydrocarbon oil as the dielectric fluid and contains it within the sparking zone. The deionised water is not suitable for conventional EDM as it causes rapid electrode wear, but its low viscosity and rapid cooling rate make it ideal for WEDM (Huntress 1978).

### 3.2.3 Hybrid machining processes

There are a number of hybrid machining processes (HMPs) seeking the combined advantage of WEDM with other machining techniques. One such combination is wire electrical discharge grinding (WEDG), which is commonly used for the micro-machining of fine rods utilized in the electronic circuitry. WEDG employs a single wire guide to confine the wire tension within the discharge area between the rod and the front edge of the wire and to minimise the wire vibration. Therefore, it is possible to grind a rod that is as small as  $5\mu\text{m}$  in diameter (Masuzawa and Tonshoff 1997) with high accuracy, good repeatability and satisfactory straightness (Masuzawa *et al.* 1985). Other advantages of WEDG include the ability to machine a rod with a large aspect ratio, maintaining the concentricity of the rod and providing a wider choice of complex shapes such as tapered and stepped shapes at various sections (Masuzawa *et al.* 1994). Several authors (Egashira and Mizutani 2002, Langen *et al.* 1995, Masuzawa *et al.* 1989, Sun *et al.* 1996) have employed the WEDG process in the micro-machining of fine electrodes or pins with a large aspect-ratio, which are difficult to be



machined by traditional precision micro-machining methods such as Micro-EDM, LIGA and excimer laser drilling.

Some of the HMPs seek to improve the WEDM performance measures such as the surface integrity and the CR. For example, the ultrasonic vibration has been applied to the wire electrode to improve the SF quality together with the CR and to reduce the residual stress on the machined surface (Guo *et al.* 1997). On the other hand, the wire electrochemical grinding (WECG) process replaces the electrical discharge used in WEDG with an electrochemical solution to produce high SF quality part for a wide range of machining condition (Masuzawa *et al.* 1994). Masuzawa *et al.* (1994, 1997) compared the SF quality obtained from the WECG with WEDG, which is suitable for finishing micro-parts. A rotary axis has also been added to WEDM to achieve higher material removal rate (MRR) and to enable the generation of free-form cylindrical geometries (Qu *et al.* 2002a, Rhoney *et al.* 2002a). The effects of the various process parameters such as part rotational speed, wire feed rate and pulse on-time on the surface integrity and roundness of the part produced have been investigated in the same feasibility study (Qu *et al.* 2002b).

### 3.3 WEDM applications

This section discusses the viability of the WEDM process in the machining of the various materials used particularly in tooling applications.

#### 3.3.1 Modern tooling applications

WEDM has been gaining wide acceptance in the machining of the various materials used in modern tooling applications. Several authors (Levy and Wertheim 1988, Luo *et al.* 1992) have investigated the machining performance in the wafering of silicon and machining of compacting dies made of sintered carbide. The feasibility of using cylindrical WEDM for dressing a rotating metal bond diamond wheel used for the precision form grinding of ceramics has also been studied (Rhoney *et al.* 2002a). The results showed that the WEDM was capable of generating precise and intricate profiles with small corner radii but a high wear rate was observed on the diamond wheel during the first grinding pass. Such an initial high wheel wear rate was due to the over-protruding diamond grains, which did not bond strongly to the wheel after the WEDM process (Rhoney *et al.* 2002b). The machining of permanent NdFeB and 'soft' MnZn ferrite magnetic materials used in miniature systems, which requires small magnetic parts, was studied by comparing it with the laser-cutting process (Kruusing *et*

*al.* 1999). It was found that the WEDM process yielded better dimensional accuracy and SF quality but had a slow CR, 5.5 mm/min for NdFeB and 0.17 mm/min for MnZn ferrite. A study was also done to investigate the machining performance of micro-WEDM used to machine a high aspect ratio meso-scale part using a variety of metals including stainless steel, nitronic austentic stainless, beryllium copper and titanium (Benavides *et al.* 2002).

### 3.3.2 Advanced ceramic materials

The WEDM process has also evolved as one of the most promising alternatives for the machining of advanced ceramics. Sanchez *et al.* (2001) provided a literature survey on the EDM of advanced ceramics, which have been commonly machined by diamond grinding and lapping. In the same paper, they studied the feasibility of machining boron carbide ( $B_4C$ ) and silicon infiltrated silicon carbide (SiSiC) using EDM and WEDM. Cheng *et al.* (1996) also evaluated the possibility of machining  $ZrB_2$  based materials using EDM and WEDM whereas, Matsuo and Oshima (1992) examined the effects of conductive carbide content, namely niobium carbide (NbC) and titanium carbide (TiC), on the CR and surface roughness of zirconia ceramics ( $ZrO_2$ ) during WEDM. Lok and Lee (1997) have successfully machined sialon 501 and aluminium oxide-titanium carbide ( $Al_2O_3$ -TiC). However, they realised that the MRR was very low as compared to the cutting of metals such as alloy steel SKD-11 and the surface roughness was generally inferior to the one obtained with the EDM process. Dauw *et al.* (1990) explained that the MRR and surface roughness were not only dependent on the machining parameters but also on the material of the part.

An innovative method of overcoming the technological limitation of the EDM and WEDM processes requiring the electrical resistivity of the material with threshold values of approximately 100  $\Omega/cm$  (Konig *et al.* 1988) or 300  $\Omega/cm$  (Firestone 1988) has recently been explored. There are different grades of engineering ceramics, which Konig *et al.* (1988) classified as non-conductor, natural-conductor and conductor, which is a result of doping non-conductors with conductive elements. Mohri *et al.* (1996) brought a new perspective to the traditional EDM phenomenon by using an assisting electrode to facilitate the sparking of highly electrical-resistive ceramics. Both the EDM and WEDM processes have been successfully tested diffusing conductive particles from assisting electrodes onto the surface of sialon ceramics assisting the feeding the electrode through the insulating material. The same technique has also been experimented on other types of insulating ceramic materials including



oxide ceramics such as  $\text{ZrO}_2$  and  $\text{Al}_2\text{O}_3$ , which have very limiting electrical conductive properties (Mohri *et al.* 2002).

### 3.3.3 Modern composite materials

Among the different material removal processes, WEDM is considered as an effective and economical tool in the machining of modern composite materials. Several comparative studies (Lau and Lee 1991, Lau *et al.* 1995) have been made between WEDM and laser cutting in the processing of metal matrix composites (MMC), carbon fibre and reinforced liquid crystal polymer composites. These studies showed that WEDM yielded better cutting edge quality and had better control of the process parameters with fewer workpiece surface damages. However, it had a slower MRR for all the tested composite materials. Gadalla and Tsai (1989) compared WEDM with conventional diamond sawing and discovered that it produced a roughness and hardness that was comparable to a low speed diamond saw but with a higher MRR. Yan *et al.* (2000) surveyed the various machining processes performed on the MMC and experimented with the machining of  $\text{Al}_2\text{O}_3/6061\text{Al}$  composite using rotary EDM coupled with a disk-like electrode. Other studies (Guo *et al.* 2002, Yue *et al.* 1996) have been conducted on the WEDM of  $\text{Al}_2\text{O}_3$  particulate reinforced composites investigating the effect of process parameters on the WEDM performance measures. It was found that the process parameters had little influence on the surface roughness but had an adverse effect on CR.

## 3.4 Major areas of WEDM research

The author has organised the various WEDM research into 3 major areas namely WEDM development, WEDM process optimisation together with WEDM process monitoring and control. The latter two research areas are discussed in this section.

### 3.4.1 WEDM process optimisation

Today, the most effective machining strategy is determined by identifying the different factors affecting the WEDM process and seeking the different ways of obtaining the optimal machining condition and performance. This section provides a study on the numerous machining strategies involving the design of the process parameter and the modelling of the WEDM process.

### 3.4.1.1 *Process parameters design*

The settings for the various process parameters required in the WEDM process play a crucial role in producing an optimal machining performance. This section shows some of the analytical and statistical methods used to study the effects of the parameters on the typical WEDM performance measures such as CR, MRR and SF.

#### 3.4.1.1.1 *Factors affecting the performance measures*

WEDM is a complex machining process controlled by a large number of process parameters such as the pulse duration, discharge frequency and discharge current intensity. Any slight variations in the process parameters can affect the machining performance measures such as surface roughness and CR, which are two of the most significant aspects of the WEDM operation (Alekseyev and Korenblum 1989). Suzuki and Kishi (1989) studied the reduction of discharge energy to yield a better surface roughness, while Luo (1995) discovered the additional need for a high-energy efficiency to maintain a high machining rate without damaging the wire. Several authors (Dauw and Albert 1992) have also studied the evolution of the wire tool performance affecting the machining accuracy, costs and performance measures.

The selection of appropriate machining conditions for the WEDM process is based on the analysis relating the various process parameters to different performance measures namely the CR, MRR and SF. Traditionally, this was carried out by relying heavily on the operator's experience or conservative technological data provided by the WEDM equipment manufacturers, which produced inconsistent machining performance. Levy and Maggi (1990) demonstrated that the parameter settings given by the manufacturers were only applicable for the common steel grades. The settings for machining new materials such as advanced ceramics and MMCs had to be further optimised experimentally.

#### 3.4.1.1.2 *Effects of the process parameters on the cutting rate*

Many different types of problem-solving quality tools have been used to investigate the significant factors and its inter-relationships with the other variables in obtaining an optimal WEDM CR. Konda *et al.* (1999) classified the various potential factors affecting the machining performance measures into five major categories namely the different properties of the workpiece material and dielectric fluid, machine characteristics, adjustable machining parameters, and component geometry. In addition, they applied the design of experiments



(DOE) technique to study and optimise the possible effects of variables during machining process design and development, and validated the experimental results using noise-to-signal (N/S) ratio analysis. Tarng *et al.* (1995) employed a neural network system with the application of a simulated annealing algorithm for solving the multi-response optimisation problem. It was found that the machining parameters such as the pulse on/off duration, peak current, open circuit voltage, servo reference voltage, electrical capacitance and table speed were the critical parameters for the estimation of the CR and SF. Huang *et al.* (1999) argued that several published works (Liao *et al.* 1997b, Scott *et al.* 1991, Tarng *et al.* 1995) were concerned mostly with the optimisation of parameters for the roughing cutting operations and proposed a practical strategy of process planning from roughing to finishing operations. The experimental results showed that the pulse-on time and the distance between the wire periphery and the workpiece surface affected the CR and SF significantly. The effects of the discharge energy on the CR and SF of a MMC have also been investigated (Rozenek *et al.* 2001).

#### 3.4.1.1.3 *Effects of the machining parameters on the material removal rate*

The effects of the machining parameters on the volumetric MRR have also been considered as a measure of the machining performance. Scott *et al.* (1991) used a factorial design requiring a number of experiments to determine the most favourable combination of the WEDM parameter. They found that the discharge current, pulse duration and pulse frequency were the significant control factors affecting the MRR and SF, while the wire speed, wire tension and dielectric flow rate had the least effect. Liao *et al.* (1997b) proposed an approach of determining the parameter settings based on the Taguchi quality design method and the analysis of variance. The results showed that the MRR and SF were easily influenced by the table feed rate and pulse-on time, which could also be used to control the discharging frequency for the prevention of wire breakage. Huang and Liao (2003) presented the use of Grey relational and S/N ratio analyses, which also displayed similar results demonstrating the influence of table feed and pulse-on time on the MRR. An experimental study to determine the MRR and SF for varying machining parameters has also been conducted (Rajurkar and Wang 1993). The results have been used with a thermal model to analyse the wire breakage phenomena.

#### 3.4.1.1.4 Effects of the process parameters on the surface finish

There are also a number of published works that solely study the effects of the machining parameters on the machined surface. Gökler and Ozanözgü (2000) studied the selection of the most suitable cutting and offset parameter combination to get a desired surface roughness for a constant wire speed and dielectric flushing pressure. Tosun *et al.* (2003) investigated the effect of the pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on the machined workpiece surface roughness. It was found that the increasing pulse duration, open circuit voltage and wire speed increased with the surface roughness whereas the increasing dielectric fluid pressure decreased the surface roughness. Anand (1996) used a fractional factorial experiment with an orthogonal array layout to obtain the most desirable process specification for improving the WEDM dimensional accuracy and surface roughness. Spedding and Wang (1997) optimised the process parameter settings by using artificial neural network modelling to characterise the machined workpiece surfaces, while Williams and Rajurkar (1991) presented the results of the current investigations into the characteristics of WEDM generated surfaces.

#### 3.4.1.2 Process modelling

In addition, the modelling of the WEDM process by means of mathematical techniques has also been applied to effectively relate the large number of process variables to the different performance of the process. Spedding and Wang (1997a) developed the modelling techniques using the response surface methodology and artificial neural network technology to predict the machining process performance such as CR, SF and surface waviness within a reasonable large range of input factor levels. Liu and Esterling (1997b) proposed a solid modelling method, which could precisely represent the geometry cut by the WEDM whereas, Hsue *et al.* (1999) developed a model to estimate the MRR during geometrical cutting by considering wire deflection with transformed exponential trajectory of the wire centre. Spur and Schönbeck (1993) designed a theoretical model studying the influence of the workpiece material and the pulse-type properties on the WEDM of a workpiece with an anodic polarity. Han *et al.* (2002) developed a simulation system, which accurately reproduced the discharge phenomena of WEDM. The system also applied an adaptive control, which automatically generated an optimal machining condition for high precision WEDM.



### 3.4.2 WEDM process monitoring and control

The application of the adaptive control systems to the WEDM is vital for the monitoring and control of the process. This section investigates the advanced monitoring and control systems including the fuzzy, the wire breakage and the self-tuning adaptive control systems used in the WEDM process.

#### 3.4.2.1 Fuzzy control system

The proportional controllers have traditionally been used in the servo feed control system to monitor and evaluate the gap condition during the WEDM process. However, the performance of the controllers was limited by the machining conditions, which considerably vary with the parameters settings. Kinoshita *et al.* (1976) investigated the effects of wire feed rate, wire winding speed, wire tension and electrical parameters on the gap conditions during WEDM. As a result, many conventional control algorithms based on explicit mathematical and statistical models have been developed for EDM or WEDM operations (Garbajs 1985, Huang *et al.* 1986, Pandit and Wittig 1984, Rajurkar and Wang 1990, Watanabe *et al.* 1990). Several authors (Liao and Woo 1997, Yan and Liao 1995) have also developed a pulse discrimination system providing a means of analysing and monitoring the pulse trains under the various machining conditions quantitatively. Although these types of control systems could be applied to a wide range of machining conditions, it could not respond to the gap condition when there was an unexpected disturbance (Yan and Liao 1998).

In recent years, the fuzzy control theory has been applied to WEDM process to achieve optimum and highly efficient machining. Several authors claimed that a control strategy implemented on a fuzzy logic control system captured the expert's knowledge or operator's experience in maintaining the desired machining operation (Boccadoro and Dauw 1995). In addition, the fuzzy logic controller did not require any comprehensive mathematical models adapting to the dynamic behaviour of the machining operation (Yan *et al.* 1999). Several authors (Liao and Woo 1998, Yan and Liao 1998) proposed the sparking frequency monitoring and adaptive control systems based on the fuzzy logic control and the adjusting strategies, which could be applied to a wide range of machining conditions. Liao and Woo (2000) also designed a fuzzy controller with an online pulse monitoring system isolating the discharging noise and discriminating the ignition delay time of each pulse. EDM pulses can be classified into open, spark, arc, off or short, which are dependent on the ignition delay

time, and have a direct influence on the MRR, SF, electrode wear and accuracy of the part (Cogun 1990, De Bruyn and Pekelharing 1982).

### 3.4.2.2 Wire inaccuracy adaptive control systems

The occurrence of wire breakage during WEDM is one of the most undesirable machining characteristics greatly affecting the machining accuracy and performance together with the quality of the part produced. Many attempts have made to develop an adaptive control system providing an online identification of any abnormal machining condition and a control strategy preventing the wire from breaking without compromising the various WEDM performance measures. This section reports research from a collection of published work involving the adaptive control of wire breakage, wire lag and wire vibration.

#### 3.4.2.2.1 Wire breakage

A wide variety of the control strategies preventing the wire from breaking are built on the knowledge of the characteristics of wire breakage. Kinoshita *et al.* (1982) observed the rapid rise in pulse frequency of the gap voltage, which continued for about 5-40 ms before the wire breaks. They developed a monitoring and control system that switched off the pulse generator and servo system preventing the wire from breaking but it affected the machining efficiency. Several authors (Kunieda *et al.* 1990, Shoda *et al.* 1992) also suggested that the concentration of electrical discharges at a certain point of the wire, which caused an increase in the localised temperature resulting in the breakage of the wire. However, the adaptive control system concentrating on the detection of the sparking location and the reduction of the discharge energy was developed without making any considerations to the MRR. The breakage of the wire has also been linked to the rise in the number of short-circuit pulses lasting for more than 30 ms until the wire broke (Tanimura *et al.* 1977).

Other authors (Rajurkar *et al.* 1991) argued that the wire breakage is correlated to the sudden increase in sparking frequency. It was also found that their proposed monitoring and control system based on the online analysis of the sparking frequency and the real-time regulation of the pulse off-time affected the MRR. Liao *et al.* (1997a) remedied the problem by relating the MRR to the machining parameters and using a new computer-aided pulse discrimination system based on the pulse train analysis to improve the machining speed. Whereas Yan and Liao (1996a, 1996b) applied a self-learning fuzzy control strategy not only to control the



sparking frequency but also to maintain a high MRR by adjusting in real time the off-time pulse under a constant feed-rate machining condition.

The breaking of the wire is also due to the excessive thermal load producing unwarranted heat on the wire electrode. Most of the thermal energy generated during the WEDM process is transferred to the wire while the rest is lost to the flushing fluid or radiation (Rajurkar *et al.* 1991). However, when the instantaneous energy rate exceeds a certain limit depending on the thermal properties of the wire material, the wire will break. Several authors (Dekeyser *et al.* 1985, Jennes *et al.* 1984, Obara *et al.* 1995) investigated the influence of the various machining parameters on the thermal load of the wire and developed a thermal model simulating the WEDM process. In addition to the sparking characteristics or the temperature distribution, the mechanical strength of the wire also has a significant effect on the occurrence of the wire breakage. Luo (1999) claimed that the wire material yielding and fracture contributed to the wire breakage, whilst an increase in temperature aggravates the failure process.

#### 3.4.2.2.2 Wire lag and wire vibration

The main factors contributing to the geometrical inaccuracy of the machined part are the various process forces acting on the wire causing it to depart from the programmed path. These forces include the mechanical forces produced by the pressure from the gas bubbles formed by the plasma of the erosion mechanism, axial forces applied to straighten the wire, the hydraulic forces induced by the flushing, the electro-static forces acting on the wire and the electro-dynamic forces inherent to the spark generation (Dauw and Beltrami 1994, Kinoshita *et al.* 1984).

As a result, the static deflection in the form of a lag effect of the wire is critically studied in order to produce an accurate cutting tool path. Several authors (Huang and Liao 1997, Luo 1999, Puri and Bhattacharyya 2003) performed a parametric study on the geometrical inaccuracy of the part caused by the wire lag and attempted to model WEDM process mathematically. Wire lag is the difference between the actual and the intended wire positions. Whereas, Beltrami and Dauw (1996) monitored and controlled the wire position online by means of an optical sensor with a control algorithm enabling virtually any contour to be cut at a relatively high cutting speed. A number of geometric tool motion compensation methods, which increased the machining gap and prevented gouging or wire breakages when cutting

areas with high curvatures such as corners with small radii have also been developed (Dekeyser and Snoeys 1989, Wang and Ravani 2003). Lin *et al.* (2001) developed a control strategy based on the fuzzy logic to improve the machining accuracy and concentrated sparking at corner parts without affecting the cutting feed rates.

In addition, the dynamic behaviour of the wire during WEDM is also restrained to avoid cutting inaccuracies. There were a few discussions on the design and development of a monitoring and control system for compensating the behaviour of the wire vibration (Enache and Opran 1993, Rajurkar *et al.* 1991). Dauw *et al.* (1989) also reported that the vibration of the wire could be substantially reduced when the wire and the wire guides were completely submerged in the working tank filled with deionised water. Several authors (Mohri *et al.* 1998) derived a mathematical model analysing the transient response of the wire vibration based on the force acting on the tool wire in a single discharge process. A number of authors (Rajurkar and Wang 1997, Snoeys *et al.* 1983) reviewed the research and development of the various advanced monitoring and control systems used in EDM and WEDM processes.

#### 3.4.2.3 Self-tuning adaptive control systems

In recent years, the WEDM research and development has explored control strategies adjusting to the variation in the power density required in machining a workpiece with varying thickness. Several authors (Kinoshita *et al.* 1982, Tanimura *et al.* 1977) found out that a change in the workpiece thickness during machining led to an increase in the wire thermal/power density and an eventual breaking of the wire. The power density in the gap and on the wire is defined as the ratio of discharge power to the discharge distribution length or workpiece height (Dekeyser *et al.* 1985). Rajurkar *et al.* (1994, 1997) proposed an adaptive control system with a multiple input model that monitored and controlled the sparking frequency according to the online identified workpiece height. Other authors (Huang *et al.* 1986) developed a system that involved an explicit mathematical model requiring a number of experiments and statistical techniques. Yan *et al.* (2001) used neural networks to estimate the workpiece height and the fuzzy control logic to suppress the wire breakage when a workpiece with variable height was machined.

The application of a knowledge-based control system to control the adverse WEDM conditions has also been experimented. Snoeys *et al.* (1988) proposed a knowledge-based system, which comprised of three modules, namely work preparation, machining process



control and operator assistance or fault diagnosis, enabling the monitoring and control of the WEDM process. The work preparation module determined the optimal machining parameter settings, while the operator assistance and fault diagnostics databases advised the operators and diagnose the machining errors. Thus, the capabilities of these modules increased the amount of autonomy given to the WEDM machine. Huang and Liao (2000) have also indicated the importance of the operator assistance and fault diagnostics systems for the WEDM process. They proposed a prototype artificial neural network-based expert system for the maintenance schedule and fault diagnosis of the machining process. Dekeyser *et al.* (1988) developed a thermal model integrated with an expert system for predicting and controlling the thermal overload experienced on the wire. Although the model increased the level of machine autonomy, it required a large amount of computation, which slowed down the processing speed and undermined the online control performance.

However, the study into the CAD/CAM system and the CNC for the WEDM process has shown little research interest. This is mainly due to the complex system architectural structure involving the use of the different control systems to perform the machining process and the control strategies. Yang and Park (2002) attempted to resolve the issue by designing and implementing an open architecture CNC consisting of an NC kernel for system integration and a four-constituent module for system function. The latter was made up of an operation-planning module, a motion control module, a discharge control module and a discrete I/O control module. Kruth *et al.* (1988) developed a set of modular software combining a generalised NC post-processor with a WEDM technological processor and a WEDM process-planner, allowing the system user to program any type of 5-axis WEDM machine by using off-the-shelf commercial CAD/CAM system. El-Midnay *et al.* (2000) also used similar modular software combination to provide the automatic correction for maximum taper angle and the automatic creation of the threading and tagging location. DeVries *et al.* (1990) argued that for the CAM modules and the CAPP software application software to be integrated transparently into the basic CAD/CAM system while remaining totally independently of any specific CAD/CAM system was through the use of a neutral CAD programming interface.

### 3.5 Critique

The author has classified the wide range of published works relating to the WEDM process into three major areas, namely optimising the process variables, monitoring and control the

process, and WEDM developments. This section discusses the classified research areas and the possible future research directions, illustrated in figure 3.2.

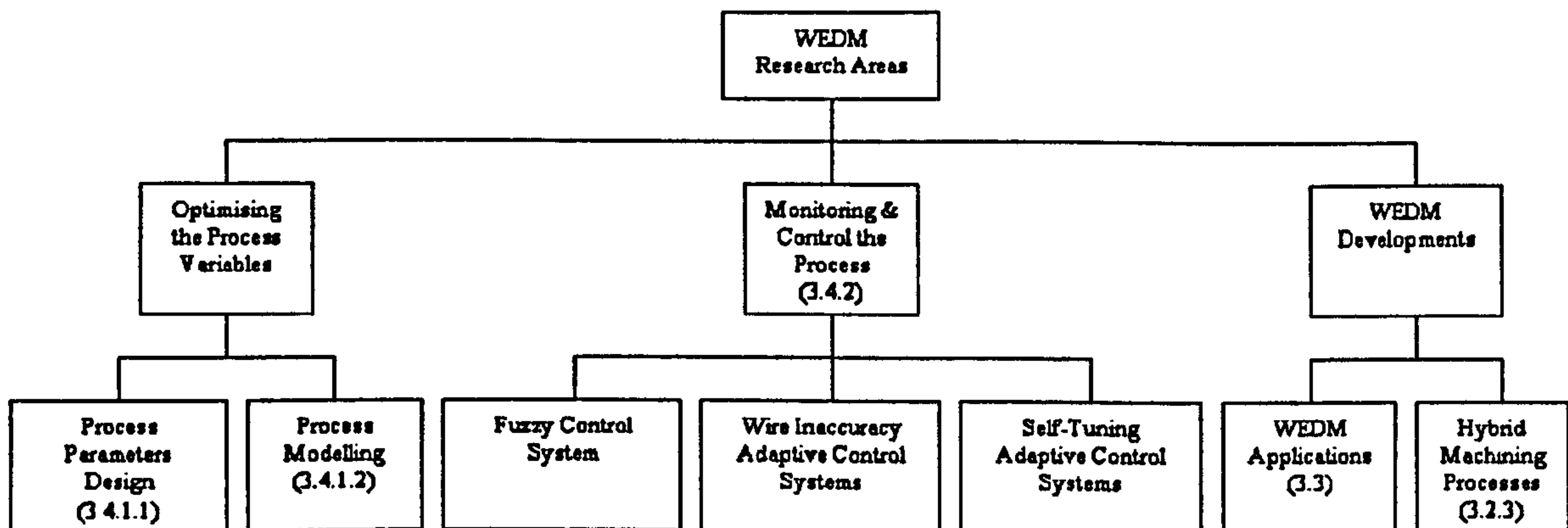


Figure 3.2 Classification of major WEDM research areas  
(corresponding section numbers are in brackets)

### 3.5.1 Optimising the process variables

The optimisation of the WEDM process often proves to be a difficult task owing to the many regulating machining variables. A single parameter change will influence the process in a complex way (Scott *et al.* 1991). Thus, the various factors affecting the machining process have to be understood in order to determine the trends of the process variation, as discussed in section 3.4.1.1. The selection of the best combination of the process parameters for an optimal machining performance involves analytical and statistical methods. However, it is very complicated to relate the input process parameters with the output performance measures and derive an optimal result using a simulation algorithm. The CR, MRR and SF are usually adopted as the measures of the machining process performance. Nevertheless, these methods provide an effective means of identifying the variables affecting the machining performance.

In addition, the modelling of the process is also an effective way of solving the tedious problem of relating the process parameters to the performance measures. As mentioned in section 3.4.1.2, several attempts have been carried out to model the process investigating into the influence of the machining parameters on WEDM performance and identifying the optimal machining condition from the infinite number of combinations. As a result, it provided an accurate dimensional inspection and verification of the process, yielding a better stability and higher productivity for the process. However, the random and complex nature of the erosion process in WEDM requires the application of deterministic as well as stochastic



techniques (Williams and Rajurkar 1991). Therefore, the optimisation of the process will remain a key research area matching the numerous process parameters with the performance measures.

### 3.5.2 *Monitoring and control the process*

Over the years, monitoring and control systems have made an important contribution in minimising the effect of disturbances on the WEDM performance. The multi-parameter machining settings have made it difficult to clearly understand and obtain the optimal machining conditions. It requires a control algorithm that is often based on explicit mathematical and statistical models to cope with the machining process. However, the application of fuzzy control logic has brought about a drastic change to the conventional way of monitoring and controlling the machining process. The fuzzy control logic is able to consider several machining variables, weigh the significant factors affecting the process and make changes to the machining conditions without applying the detailed mathematical model, as mentioned in section 3.4.2.1. In addition, the feasibility of applying an expert system capable of giving advice and solving problems has also been explored (Snoeys *et al.* 1988). Such a system would greatly appeal to the shop floor operational needs demanding unattended WEDM operation.

The risk of wire breakage and the bending of the wire have also limited the efficiency and accuracy of the WEDM process. The occurrence of the wire breakage directly reduces the already low machining speed affecting the overall productivity of the machining process. Although, the control strategies reported in section 3.4.2.2 were designed to solve the problems of wire breakage, they solely relied on the indication of the possible occurrence and generated inadequate results for investigating the root cause of the wire breakage phenomenon. These strategies might therefore be deemed to be a setback when machining a workpiece with variable heights requiring a drastic change in the machining conditions.

In addition, the wire vibrational behaviour and static deflection easily influence the geometric accuracy of the part produced. The typical solutions to these problems are often very conservative in nature by increasing the machining gap or reducing the discharge energy, which is regarded to be a main drawback for the WEDM process efficiency. Figure 3.3 shows the considerable amount of research work concentrating on the improvement of the inaccuracy caused by the wire through the application of an adaptive control system. Jennes

and Snoey (1984) believed that the traditional research purpose was not to improve machining efficiency, but to prevent wire rupture during the machining process. Hence, one possible new WEDM challenge and future work area will be steered towards attaining higher machining efficiency by acquiring a higher CR and MRR with a low wire consumption and frequency of wire breakage.

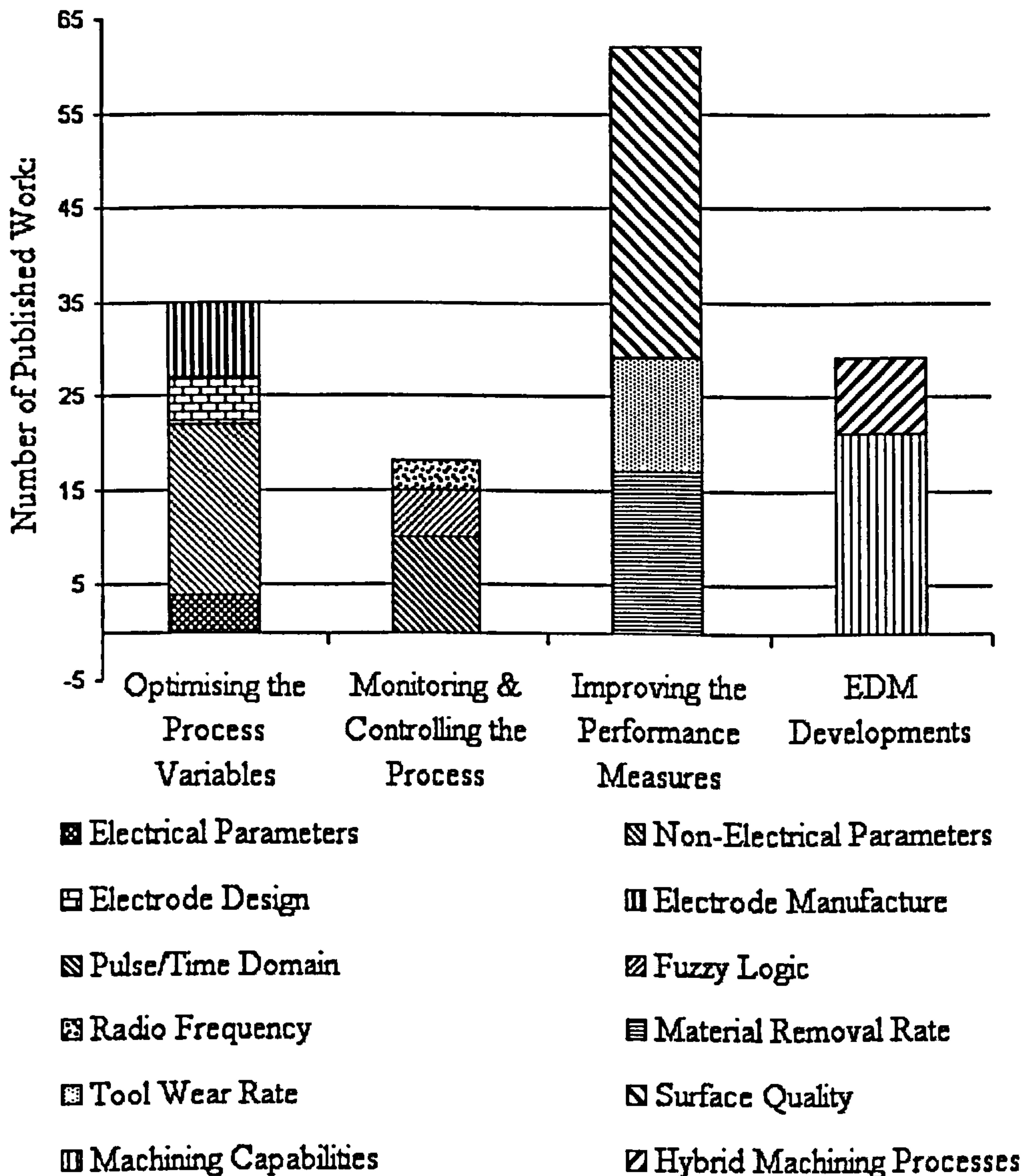


Figure 3.3 Distribution of the collected WEDM research publications

### 3.5.3 WEDM developments

The WEDM process is a suitable machining option in meeting the demands of today's modern applications. It has been commonly used in the automotive, aerospace, mould, tool and die making industries. WEDM applications can also be found in the medical, optical, dental, jewellery industries, and in the automotive and aerospace R&D areas (Stovicek 1993). Its large pool of applications, as shown in figure 3.3, is largely owed to the machining



technique, which is not restricted by the hardness, strength or toughness of the workpiece material. As mentioned in section 3.3, the machining of the HSTR, modern composite and advanced ceramic materials, which are showing a growing tendency in many engineering applications, has also been experimented. It has replaced the conventional means of machining ceramics, namely ultrasonic machining and laser beam machining, which are not only costly but damage the surface integrity of the ceramic component. However, with the introduction of over 20 non-traditional machining processes in the past 50 years and the rapid growth in the development of harder, tougher and stronger workpiece materials (Yeo *et al.* 1997), the WEDM process inevitably has to be constantly rejuvenated in order to compete and satisfy the future crucial machining requirements.

In addition, the WEDM process has sought the benefits of combining with other material removal methods to further expand its applications and improve the machining characteristics. The author has classified WEDM machine into the various physical characteristics, which clearly distinguished the different types of machine features affecting the performance measures, machining capacity and auxiliary facilities, as shown in figure 3.4. One of the most practical and precision HMP arrangements is the WEDG process used mainly to produce small size and complicated shape thin rod, which can be easily bent or broken by the lateral force when using a conventional grinding process. The precision of the CNC system is also partly responsible for the accuracy of the WEDG (Snoeys *et al.* 1986). Therefore, the HMP processes, in particular the WEDG process, will continue to receive intense research attention especially in the growing field of microelectronics circuitry manufacturing.

There is also a major push toward an unattended WEDM operation attaining a machining performance level that can be only achieved by a skilled operator. Such a goal has been partly fulfilled through the application of CNC to control the machining strategies, to prevent wire breakage and to automate the self-threading systems. An environmentally friendly and high-capacity dielectric regeneration system, which autonomously maintains the quality of the dielectric circulating within the WEDM machine, has also been experimented (Levy 1993). However, due consideration still has to be given to improving WEDM performance and enhancing the level of automation for future integration of the EDM and WEDM processes within the CIM environment (DeVries *et al.* 1990). By doing so, it would be able to reasonably meet the shortage of highly skilled EDM/WEDM operators and achieve a more cost efficient and cost effective machining operation.

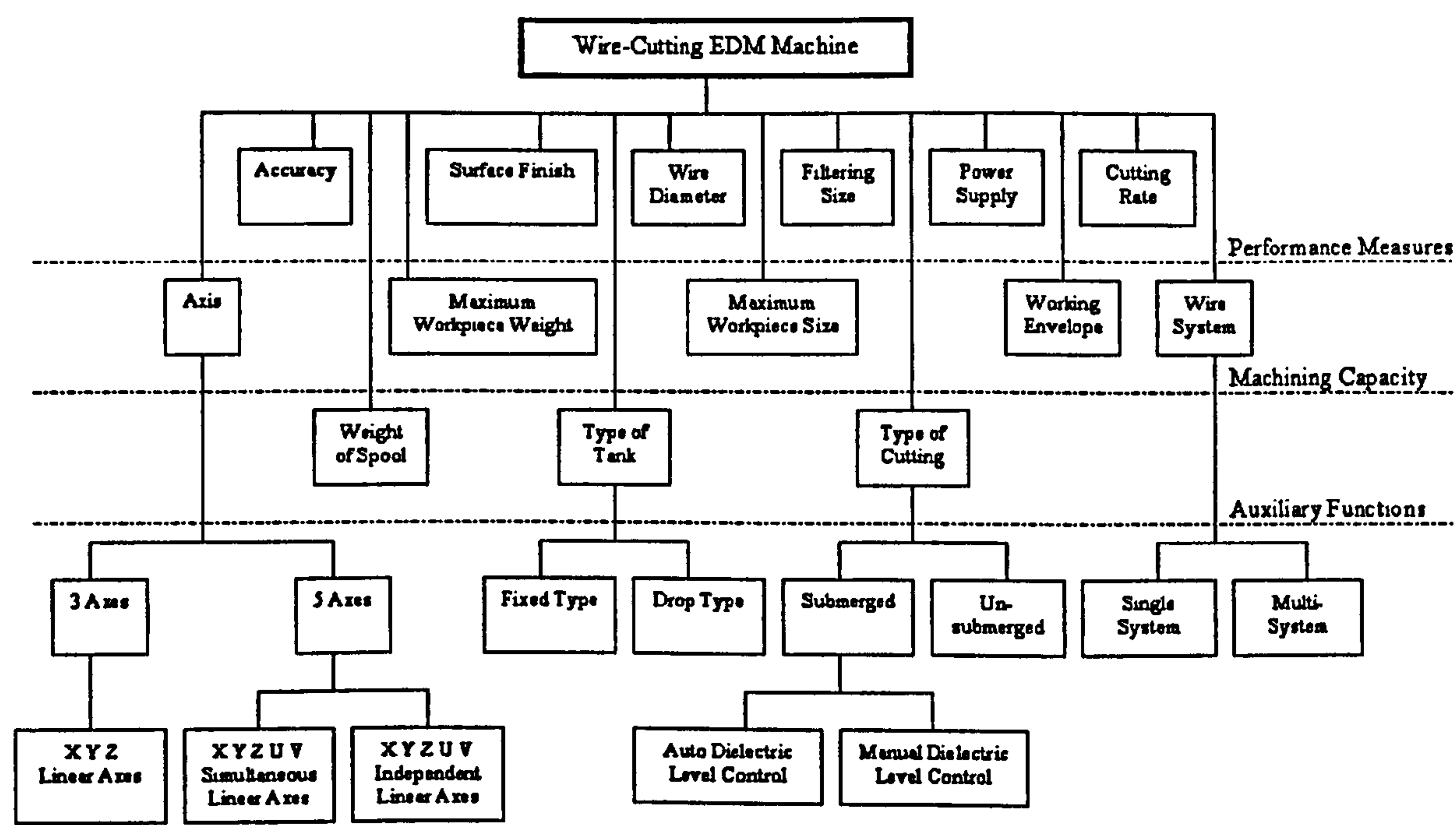


Figure 3.4 Classification of wire-cutting EDM machine

This chapter has aimed at understanding the interrelationship between the various factors affecting the machining process and identifying the optimal machining conditions. However, the true potential of these works has been confined by the use of the low-level G & M codes to program the WEDM machine. The programming/machining parameters and strategies affecting the transient WEDM sparking behaviour or the risk of wire breakages have not been adequately represented by these codes. These programming/machining functionalities are currently represented by different WEDM machine vendors using their own unique codes, see section 8.4.2. To further complicate the problem, it is not easy to gain access to the proprietary WEDM CAD/CAM and CNC system architecture, limiting the research and development into the interoperable manufacturing of WEDM parts across the CAX to CNC process chain. Thus, the implementation of STEP-NC to the WEDM process planning is a vital step of overcoming the ambiguous representation of the information relating to the machining operations. This research area has yet to be explored by the research community and is listed as one of the author's research objectives studying the implication of STEP-NC on the machining/programming capabilities of the WEDM process.



## Chapter 4

# EVOLUTION OF STEP-NC

### 4.1 Introduction

This chapter describes the evolution of STEP-NC by reviewing the conventional methods of part programming a component for CNC manufacturing. It also describes the various international efforts of specifying the data transfer standard representing and exchanging the product and manufacturing information between the different CAx and CNC systems. The major part of the chapter presents a structured view of the STEP-NC compliant information models defining the different information requirements needed to support the various CNC machining process planning activities. The final part of the chapter identifies the major research and development into STEP-NC carried out by the international STEP-NC community, mainly from Europe, Korea, Switzerland and USA.

### 4.2 Conventional NC part programming methods

This section reviews the different low level yet widely accepted conventional part programming methods.

#### 4.2.1 *Manual part programming*

The conventional methods of programming a part rely on the low level information, which is specified in G & M codes based on the ISO 6983 standard (1982), to control the machining operations. The G codes provide the machine controller with the centre line of the cutting tool path while the M codes provide the simple switching instructions for a particular mode of operation, such as coolant on/off or spindle start/stop. Other machine control information is also included in the ISO 6983 part program, such as the machining sequence (N identifier), feed (F identifier), speed (S identifier) and tool (T identifier). However, these basic commands deliver only limited information to the machine controller, excluding the valuable information such as part geometry and process plan implicated in the machine control codes, making it nothing but an executing mechanism completely unaware of the motions being executed (Suh *et al.* 2002).

Traditionally and still today, part programmers have to determine the machine control codes, which include the G & M codes together with the other machine control information for the part program by studying the engineering drawing of the component and calculating the centre line of the cutting tool path. These machine control codes have to be specified in a word address format/NC data format. The part program is then entered into and interpreted by the machine tool controller to perform the specified machining operations at the machine tool. Such a tedious manual programming process is clearly time consuming and potentially prone to human errors, especially when programming a component of complex shape. In addition, the accuracy of the machined component is compromised by the part programmer's knowledge of the machining practice and the machine tool, and their individual skills of programming a component.

#### *4.2.2 Computer-assisted part programming*

The advent of a computer-assisted part programming language in the 1950's brought several programming benefits to the traditional onerous approach of manual programming a component. It relieved the part programmer from the tedious mathematical calculation of the cutting tool path and offsets by coding the component geometry and the machine control information into a part program using the part programming language. One such language was automatically programmed tools (APT) (1987). The part program was then compiled into a machine independent data format, commonly known as the cutter location data file; thus eliminating manual programming errors. Subsequently, the cutter location data was converted into the machine specific control codes by means of a vendor-specific post-processor dedicated to a particular machine controller or machine tool. Other programming aids included the canned cycle and the subroutine or macro, which allowed the part programmer to perform a sequence of repetitive machining operations using a special preparatory command or a single group of variable parameters.

However, the use of a vendor-specific post-processor caused a major data exchange problem between different part programming languages and machine controllers. The post-processor customised the part program with vendor-specific extensions of the ISO 6983 standard for a particular model of the machine controller. This was largely due to the machine tool manufacturers producing new machining features, which could not be fully satisfied by the traditional machine control codes (Jones 1992), for example the G81 drilling canned cycle. Though the post-processors were specific to individual machine controllers, the basic G & M



codes were implemented to perform the drilling canned cycle, such as the G00 rapid traverse and G01 linear interpolation commands. However, the NC data format and the proprietary technique behind the canned cycle vary from machine vendor to machine vendor. In order to facilitate the processing of a wide variation of machine controllers, part programming languages were supplied with a library of vendor-specific post-processors, which were also required in the CAD/CAM method of programming a component, as shown in figure 4.1.

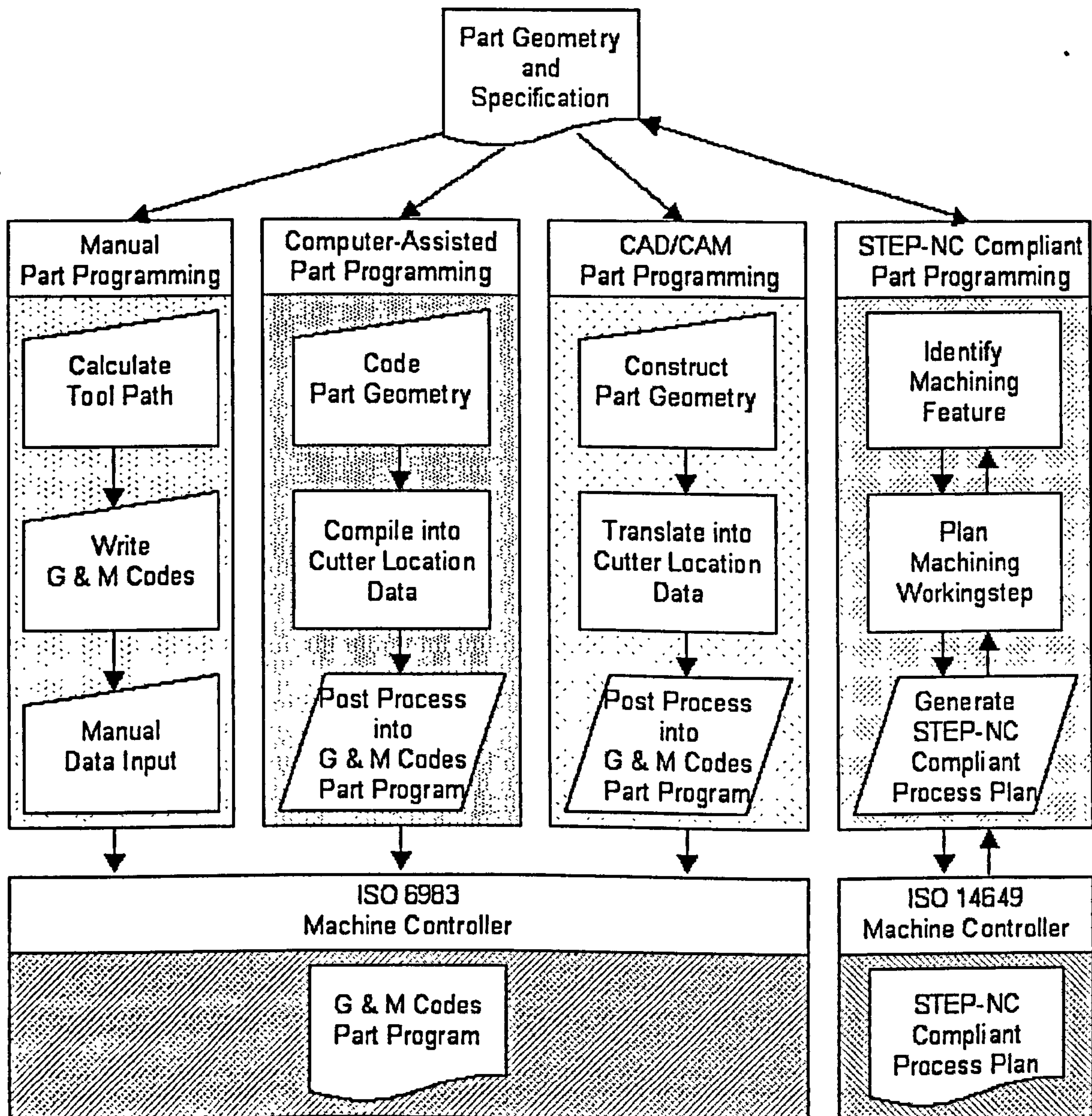


Figure 4.1 Evolution of NC Technology (adapted from McMahon and Browne 1998)

#### 4.2.3 CAD/CAM part programming

The only major difference between the computer-assisted and the CAD/CAM methods of part programming is in the translation of the cutting tool path from the component geometry. In CAD/CAM part programming, the cutter location data is directly translated from the CAD

part geometry using a CAM program. As a result, it removes the need to encode the part geometry and the tool motion, eliminating the risk of errors in interpreting the geometry and reducing the time taken in preparing the cutting tool path (McMahon and Browne 1998). The other advantages in using a CAD/CAM system include the visual verification of the part program, which provides a graphical display of the machining operation, and the editing of the part program, which uses the interactive editing graphics.

Although, both the part programming language and the CAD/CAM system rely on the part geometry to obtain machine control codes, both methods do not support complex part geometry, such as spline interpolation. The machine control codes have been formalised from the more than 30-year-old ISO 6983 standard, which only supports simple tool trajectories that are inadequate in satisfying the demands of controlling 5 or more axes of machining. As a result, machine controller vendors add their own codes to the existing G & M codes. This is further complicated by the one-way flow of information discouraging any editing from the downstream to the upstream design and manufacturing computing software applications, referred in figure 4.1. All the conventional routes of part programming have the similar information flow problem largely due to the traditional means of representing and exchanging process information between different design and manufacturing software systems.

### 4.3 Data transfer standards

This section describes a few data transfer standards relying on the neutral data format to address the concept of communicating product data among the different CAx systems, namely the IGES, PDDI and PDES standards.

#### 4.3.1 Data transfer format

Traditionally, vendors made CAD packages with a diverse range of functions and performances, which are dependent on algorithms with closed and proprietary data formats, as a key to control and retain the ownership of a customer base (Thilmany 2001). As a result, these CAD packages create communication problems of translating product data between the corresponding systems due to the presence of vendor-specific NC data formats. The problem becomes more apparent when a new system is added to an existing system, which increases the number of translators required to directly convert and transfer the data to the newly added system, refer to figure 4.2a. The total number of translators needed is represented by the formula  $N(N-1)$ , where  $N$  is the number of systems involved in the transferring of the files



(Bhandarkar *et al.* 2000). This is in complete contrast to the indirect means of translating the data by using an intermediary file called the neutral data file.

The neutral data format seeks to offer an equitable solution of integrating disparate systems together to collectively perform an application. It involves using a pair of indirect translators, which are independent of the existing and future systems, to pre-process the native data format from the source system into the neutral data format and subsequently post-process the neutral format into the native format of the target system, as shown in figure 4.2b. Since, the indirect translation method does not require constructing a new interface whenever a new system is installed, the cost incurred is relatively low as compared to the direct method. Moreover, the indirect translator philosophy protects against system obsolescence and eliminates dependence on a single-system supplier (Zeid 1991), thereby promoting the integration among different design and manufacturing software systems.

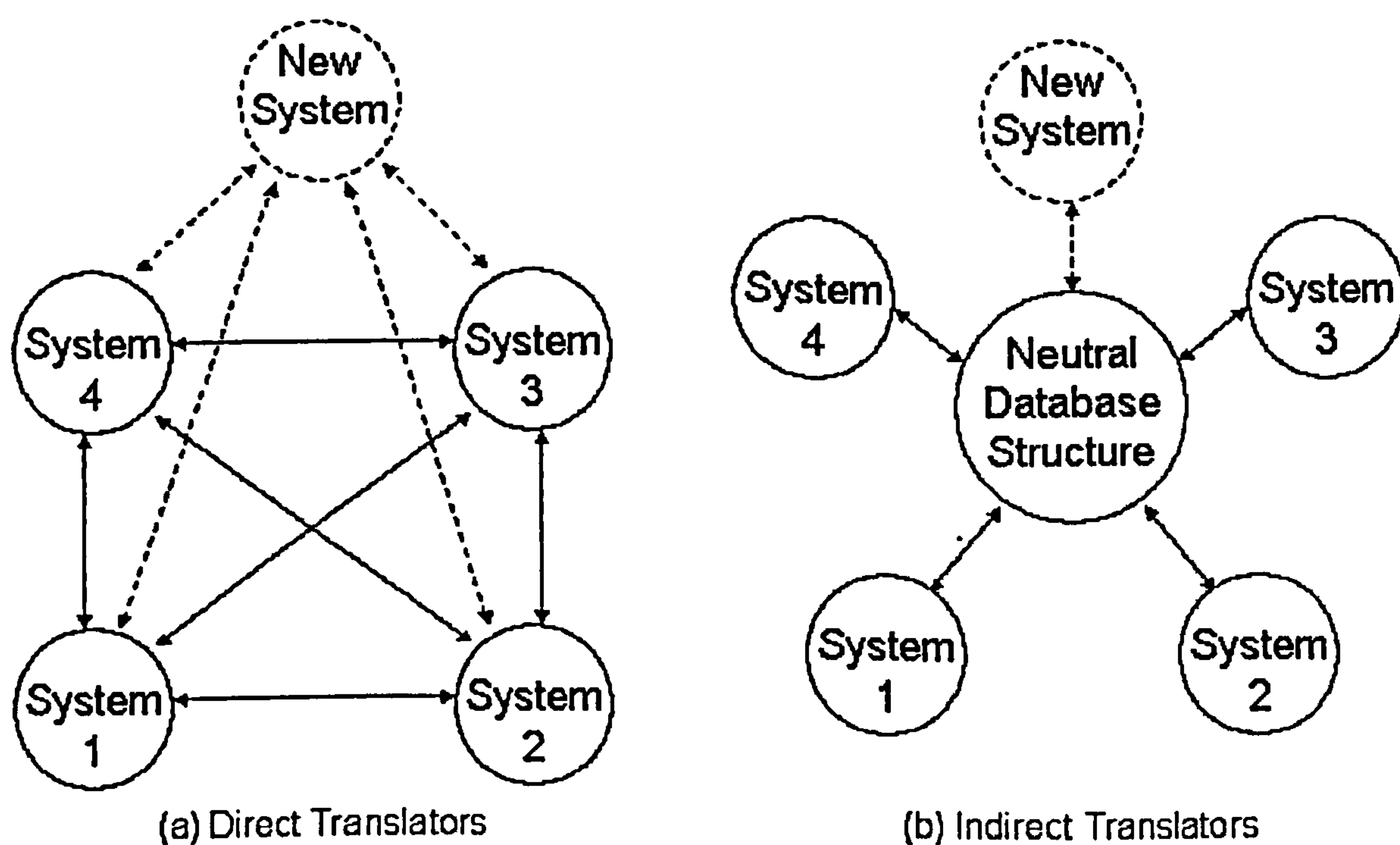


Figure 4.2 Methods of exchanging modelling data among dissimilar CAD/CAM systems (Zeid 1991)

The development of the neutral data format is also prompted by the industrial move toward the automation of NC part programming. It aims to enable the use and reuse of the valuable product and manufacturing data among the different design and manufacturing software systems encountered over the entire product life cycle. The structure of the neutral database covers a minimum definition of the design and manufacturing intent so as to satisfy the

information requirements to machine a part. More importantly, the common underlying data structure of the part programming system must be extensive so that it can provide the data input required for each new function and accept the results of each new function (Young 1994).

#### 4.3.2 IGES

The IGES (initial graphics exchange specification) was the first data exchange effort targeted towards the transfer of product data between corporate systems and suppliers'/customers' systems. Its early version 1.0 (ANSI-Y14.26M 1981) defined a collection of information structures, which could be classified into geometry and non-geometry entities, to be transferred between systems by using a vendor independent format, ASCII (American Standard Code for Information Interchange). ASCII standard (1991) code is used for information interchange among data processing systems and data communications systems in the United States. The geometry entities consisted of the definition of simple physical shapes, such as curve, solid model and part feature, while the non-geometry entities provided the graphical characteristics of the entities, such as dimension and text (Bhandarkar *et al.* 2000). However, due to the then 80-column file format, the size of the neutral file was found to be large requiring a long transmission time between different software systems. The file was also very ambiguous due to the complicated way of arranging the data. Such limitations had been widely dismissed as highly inefficient, which prompted the development of the German DIN 66301 (1986), which allowed a higher order of representing the surface geometry, and the French Z 68300 (1985), which had a more compact format.

Although IGES has alleviated the problems in the later version, it has yet to be accepted as a formal definition language for data exchange. The revised version 5.3 (ANSI-US-PRO/IPO-100 1996) has merely increased the coverage of the specification by extending the complexity of the entities, such as the spline curves and surfaces, to support the growing number of CAD applications. However, vendor industrial practice was originally to only interpret and implement those entities that were relevant to their systems, which in effect caused discrepancies with systems executing IGES on a different set of entities. This was further made inconsistent by the insufficient number of conformance clauses resulting in an incomplete translation or loss of information. All of these issues, which have been overlooked by the IGES community, have contributed to the development of the STEP standard (Reed *et al.* 1990).



### 4.3.3 PDDI & PDES

The eventual need to develop an extensive data transfer standard incorporating the essential information required by the various product life cycle related applications has been attempted by a number of organisations. The PDDI (product definition data interface) was developed by McDonnell Aircraft Corporation from the ICAM (integrated CAM) project (ICAM 2005, Shah and Rogers 1988), which expanded the IGES concepts through the application of manufacturing information into its standard format. The standard format was intended to serve as the information interface between engineering and manufacturing activities, such as process planning, NC programming, NC verification, quality assurance, tool design, robotics and other (Goldstein *et al.* 1998, Zeid 1991). Although the PDDI standard format could cater for discrete mechanical components of either sheet metal, turned, composite and machined configuration, it could not deal with component assemblies.

The PDES (product data exchange specification) was initialised by the IGES organisation aiming to establish a mechanism for complete product model data exchange (Shah and Rogers 1988). It was based on the discipline of information modelling by focusing on both the logical information being captured and the physical mechanism of data exchange. PDES was designed to facilitate the data exchange within a number of applications including architecture, engineering, construction, mechanical features, finite element modelling and printed circuit board manufacture. The research into the exchange of product definition data was not only confined to the US, in 1984 a five-year ESPRIT (European strategies programme for research into information technology) research project called CAD\*I (CAD Interfaces) led by Germany, focused on European developments in data exchange standards (Zeid 1991). CAD\*I mainly concentrated on product model data exchange for finite element analysis based on the use of schemas formally defined by using a data modeling language (Kemmerer 1999).

However, it was the ISO Technical Committee 184/Sub-Committee 4 (TC184/SC4) that has driven the effort to replace the bewildering array of emerging data exchange standards with an agreed international standard of representing and exchanging the product data. TC184/SC4 has coordinated and drawn together several world-wide projects including the VAD-FS (Verband Der Automobilindustrie Flächen Schnittstelle) (1986), SET (Standard d'Echange et de Transfert) (1985), PDDI and PDES into a single unified global standard specified as ISO 10303 (1994) or more commonly known as STEP.

## 4.4 STEP data transfer standard

This section provides the fundamentals of the STEP data transfer standard. It also describes the formal data specification language called EXPRESS and the STEP data model and structure.

### 4.4.1 STEP fundamentals

STEP provides a complete representation of the product information together with the mechanisms and definitions enabling product data to be exchanged among the different computer systems encountered during the product life cycle. Unlike IGES, providing product information merely for drawing and 3D modelling purposes, STEP addresses the issue of sharing product information among the diversified engineering applications, such as design, analysis, process planning, manufacturing, maintenance and disposal. The product information aims to include not only the geometrical representation of the product, but also the process models, such as the manufacturing features, tooling, manufacturing strategies and manufacturing processes for the various stages of product development (Hardwick 2000). Thus, it acts as an effective means of fusing the manufacturing efforts among corporate partners and suppliers across the diverse computer environments through the use of the same product information.

STEP became a full standard in 1994 and has since gained considerable acceptance by the industry, notably in the aerospace and defence, automotive and ship building, electronics and manufacturing sectors (Smith 2002). This is largely due to STEP drawing on the experiences and improvements of its predecessors through a number of areas namely (Owen 1993):

- *Formal specification language* – uses an information modelling methodology called EXPRESS (ISO10303-11 2004) to specify the information model in STEP.
- *Three-layer architecture* – comprises of
  - i. Logical layer containing the implementation methods, which describes how EXPRESS is mapped to the physical files and other storage mechanisms,
  - ii. Physical layer containing the resource information models, which provides the context-independent information, such as the description of the geometry, topology or product structure, and
  - iii. Application layer containing the Application Protocols (APs), which holds information related to a particular application domain, such as draughting or electrical product modelling.



- *Conformance clauses* – includes conformance testing methodology and a series of test sets to ensure conformance to the standard.

The STEP standard has also made a clear distinction between the information models and the infrastructure in order that the product data models can be applied in a number of ways. For example, it is organised into the APs with a unique sets of entities chosen for specific product, process or industry. Figure 4.3 shows the STEP standard architecture, in which the information models are depicted in shades and the infrastructure is not shaded.

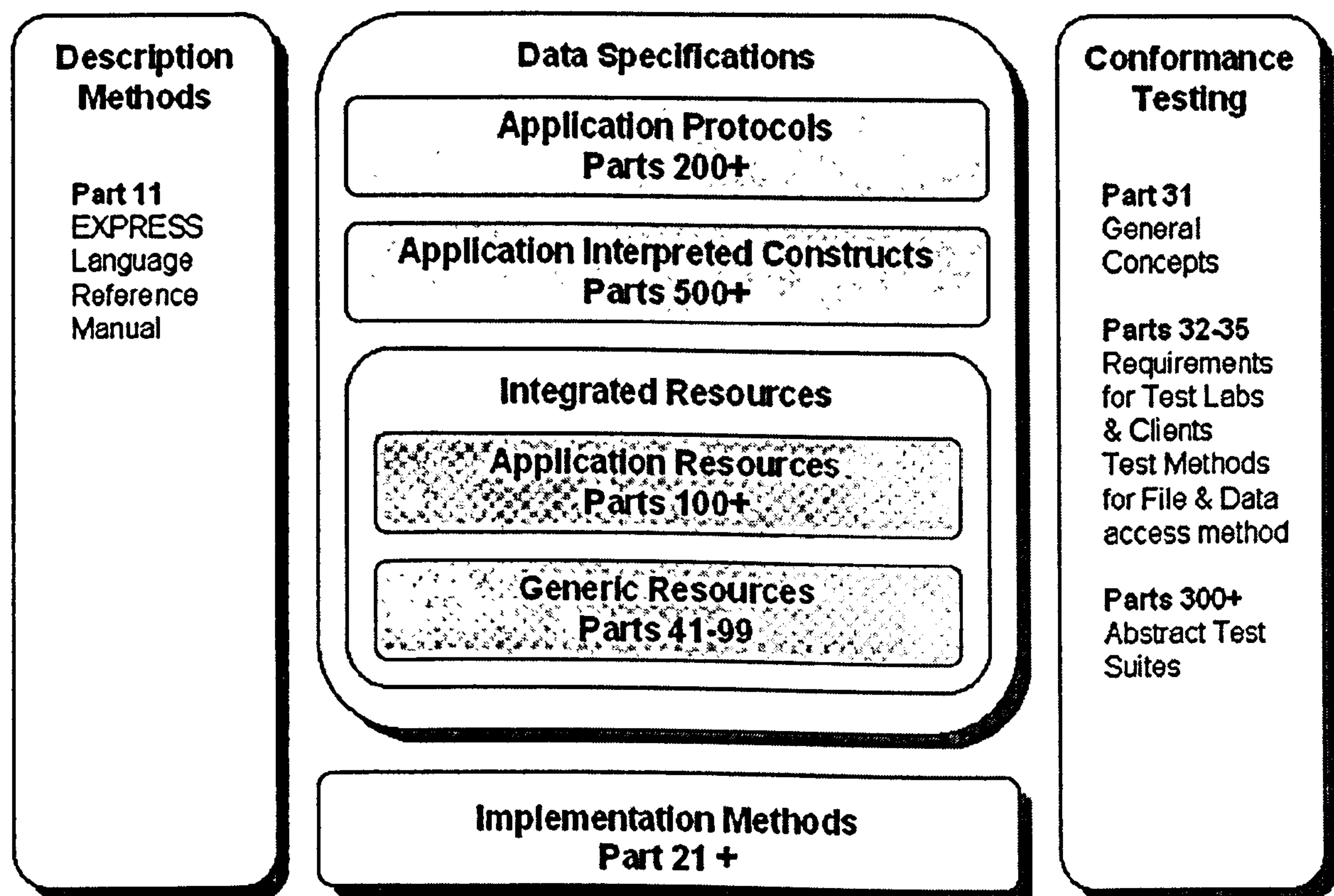


Figure 4.3 STEP architecture (Feeney *et al.* 2003)

#### 4.4.2 STEP data model and data structure

The STEP standard is being progressively developed as a series of separate standards called parts. Each part is logically classified as a class representing the different product data models covering the full life cycle of a product. As a result, the large size of the standard is broken up into a number of classes making it simple for the CAD vendors to implement the appropriate part of the standard. These classes include (ISO10303-1 1994, McMahon and Browne 1998):

- Introductory (Parts 1-9) currently comprising of Part 1 providing an introduction to the concepts and fundamental principles of STEP.
- Description methods (Parts 11-19) comprising of Part 11 and 12 relating to the standardised method, known as the EXPRESS language used to describe STEP entities.
- Implementation methods (Parts 21-9) describing how EXPRESS is mapped to physical files and other storage mechanisms.
- Conformance testing methodology and framework (Parts 31-9) providing methods for testing implementations, and test suites to be used during conformance testing.
- Integrated resources (IRs) (Parts 41-99, 101-99) including generic resources such as geometry and structure representation (41-99), and application resources such as draughting and finite element analysis (101-99).
- Application Protocols (Parts 201-99) describing implementations of STEP specific to particular industrial applications, and are associated with implementation methods to form the basis of a STEP implementation.
- Abstract test suites (Parts 301-99) providing test suites for each of the APs.
- Application interpreted constructs (Parts 501-) describing various model entity constructs, and specific modelling approaches.

#### 4.4.2.1 *EXPRESS language*

EXPRESS is a formal information modelling language, which is used to specify the semantics of the product data model common to many applications. The semantics of the data model are expressed in an object-oriented manner facilitating the extension of the data model upon any changes or updates. Therefore, it is easy for the engineers or programmers to assemble a large product model created in different CAD systems. The basic element of the EXPRESS language is the entity, which specifies the characteristics, constraints and relationship with other entities (ISO10303-11 2004). It provides a far richer set of language tools for expressing the semantics of the data types within a translation scheme than the standard general-purpose modelling methodologies, such as NIAM and IDEF1X, which only aid in the conceptual definition of the relational databases (Eastman 1994). The use of these parts or so called 10's series of the STEP standard produces a consistent representation and avoids ambiguity of the product information between the different CAD systems. The graphical notation of the entity and attribute relationship is also defined in the ISO 10303-11 standard and is called EXPRESS-G (2004).



#### 4.4.2.2 *Implementation methods and conformance testing*

STEP places a high emphasis on the implementation and conformance of the complete information model supporting a specific application. The implementation methods class or the 20's series define the exchange file structure and the application programming interface to the STEP database. For example:

- ISO 10303-21 (2002) - clear text encoding of the exchange structure.
- ISO 10303-22 (1998) – standard data access interface (SDAI) specification.
- ISO/TS 10303-27 (2000) - Java programming language binding to the SDAI with Internet/Intranet extensions.
- ISO/TS 10303-28 (2003) - XML (extensible markup language) representations of EXPRESS schemas and data

The latter two parts of the STEP standard have been momentarily gaining research attention due to the acceptance of Internet-based technology enabling Web based manufacturing or e-manufacturing. More companies are adding the requisite machine intelligence, Web connectivity, and e-commerce and collaborative manufacturing software systems for implementing e-manufacturing (Hardwick 2001, Waurzyniak 2001, Xu and He 2004).

Conformance testing is covered by two series of 10303 parts, namely the conformance testing methodology and framework, and abstract test suites, which will be discussed in section 4.4.2.5. The conformance testing methodology and framework or the 30's series define the procedures and tools required to undertake the data and application verification, e.g. ISO 10303-31 (1994) specifies the general concepts for the conformance testing methodology and framework. The foundation for the conformance testing concepts, methods and vocabulary were modelled after the ISO 9646 Open Systems Interconnection (OSI) standards incorporating a built-in basis for assessing conformance of implementations into the STEP architecture (Kemmerer 1999).

#### 4.4.2.3 *Integrated resources*

The data content defined in this part of the STEP standard provides the building block for the development of the APs. The 40-90's series include the generic resource information models, which support general applications, e.g. ISO 10303-41 (2000) specifies the fundamentals of product description and support, ISO 10303-42 (2003) specifies the geometric and topological representation. As for the 100's series, they include the application resources, which support

a specific application or a class of application, e.g. ISO 10303-101 (1994) applies to draughting, while ISO 10303-104 (2000) applies to finite element analysis. The product data is represented in an application-independent format and is only implemented via an AP.

#### 4.4.2.4 Application Protocol (AP)

The APs, or the 200's series, are used to specify the representation of product information for one or more particular life cycle stages of a specific product class. It is expected that many APs may be developed to support a wide range of industrial applications that STEP will serve. They are constructed from a set of IRs, which defines the fundamental constructs that can be specialised and applied for a wide variety of applications such as:

- AP 203 (1994) - configuration controlled 3D designs of mechanical parts and assemblies
- AP 214 (2003) - core data for automotive mechanical design processes
- AP 219 (2002) - dimensional inspection information exchange
- AP 224 (2000) - mechanical product definition for process planning using manufacturing features
- AP 240 (2003) - Process plans for machined products

The APs also include the context in which they are to be implemented, and a mapping indicating which particular task they perform in the application. This is part of the basic strategy of the STEP standard specifying the lower-level APs defined within a common framework, allowing them to be integrated at the enterprise level (Eastman 1994). APs are based on these four main ideas (Bloor and Owen 1991):

- i. Scope and context of application,
- ii. ARM (application reference model) defining the information requirements needed for a particular application,
- iii. AIM (application interpreted model) satisfying the information requirements given in the ARM by using the STEP constructs, and
- iv. Conformance requirements and test procedures for compliance with the APs.

The primary difference between the ARM and the AIM is the degree to which they use the STEP representation methods and technical architecture (Feeney *et al.* 2003). ARM is defined as an information model that describes the information requirements and constraints of a specific application context (ISO10303-1 1994). Whereas, the AIM is defined as an



information model that uses the integrated resources necessary to satisfy the information requirements and constraints of an application reference model within an AP (ISO10303-1 1994). Such a difference has an enormous implication on the implementation of STEP-NC, which will be discussed in the section 4.5.3.

#### 4.4.2.5 *Abstract test suites*

The abstract test suites are standardized in the ISO 10303-300 series containing the set of abstract test cases to support the conformance testing of an implementation for an AP. Each abstract test case specifies input data to be provided to the implementation under test, along with information on how to assess the capabilities of the implementation (Kemmerer 1999). STEP developers standardized the abstract test suites in order to alleviate the informal development of multiple test suites by various testing groups (McKay *et al.* 1994). One such abstract test suite is the ISO/TS 10303-304 (2001) for mechanical design using boundary representation.

#### 4.4.2.6 *Application interpreted constructs*

The application interpreted constructs are reusable groups of information-resource entities that make it easier to express identical semantics in more than one AP (Nell 2005). An interpreted construct is a common interpretation of the integrated resources that supports interoperability among the APs. For example, ISO 10303-514 (1999) specifies the application interpreted construct, which specialises the generic constructs from ISO 10303-42, for the definition of an advanced boundary representation solid with explicit topology and elementary or free-form geometry.

### 4.5 **STEP-NC compliant machining process planning**

This section reviews the basic fundamentals of STEP-NC, which seeks to standardise the information about CNC machining by adding to parts represented in the STEP product data model.

#### 4.5.1 *STEP-NC fundamentals*

ISO 14649 or more informally known as STEP-NC aims to offer a solution to overhaul the conventional routes of part programming a component. It is an extension of STEP that defines data representation *workingsteps*, or a library of specific operations that might be performed on a CNC machine tool (Hardwick and Loffredo 2001). Figure 4.4 shows the

relationship between the STEP and the STEP-NC standards. STEP-NC is the end result of the a project developed by the ISO TC184/SC1 and TC184/SC4 with the combined support of the IMS (Intelligent Manufacturing System) project, which was completed in 2001, named STEP-NC in Europe and Asia, and Super Model in the USA (Allen *et al.* 2003). It seeks to specify all the information requirements needed to carry out the different CNC machining processes by enhancing the design information with the associated manufacturing information. These information requirements include the billet descriptions, inspection quality tolerances, manufacturing features, set up procedure and tooling requirement. STEP-NC uses an external process plan generator making use of feature, process and cutting tool recognition tools to create the machining instructions. The end result is a detailed high-level process plan presented as a *workplan* consisting of several *workingsteps* needed to execute the various CNC machining operations. The term 'process plan' is used throughout the thesis to refer to the richer data output produced from the STEP-NC route of part programming.

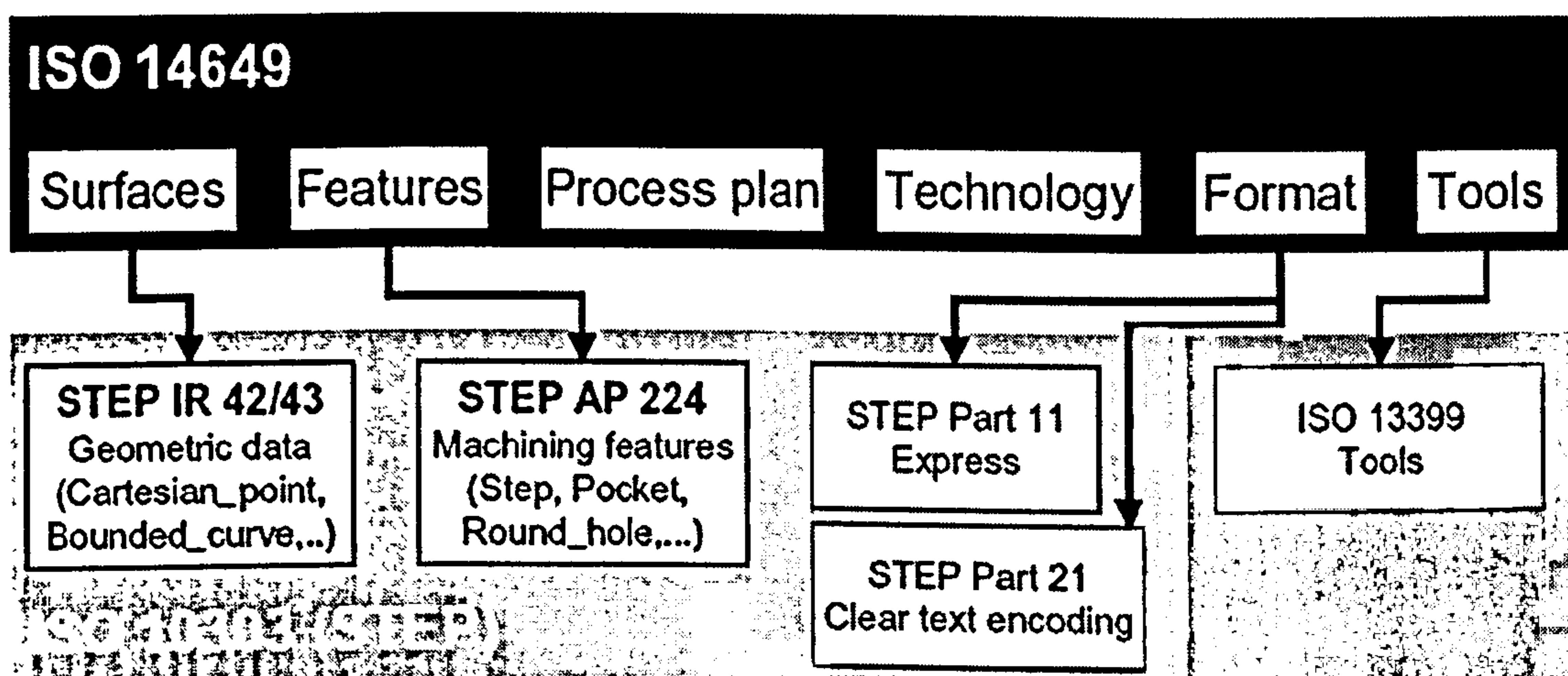


Figure 4.4 The relationship between  
STEP (ISO 10303) and STEP-NC (ISO14649) (Weck and Wolf 2003)

The main appealing feature of STEP-NC is the removal of the post-processor from the part-programming route. Figure 4.5 shows the major differences between the conventional and the STEP-NC route of part programming. STEP-NC eliminates the transitional steps of post-processing the vendor-specific part program, which relies on the G & M codes to execute a machining operation. It aims to generate a machine-independent process plan that describes in stages when a particular machining feature should be machined according to the associated machining process parameters. Moreover, the STEP-NC route of part programming facilitates a bi-directional flow of information enabling engineering changes made at the shopfloor to be updated to the design department. This is possible due to the neutral data



format of representing the design and manufacturing intent, which simplifies the exchange of product information between dissimilar CAD, CAM and CNC systems.

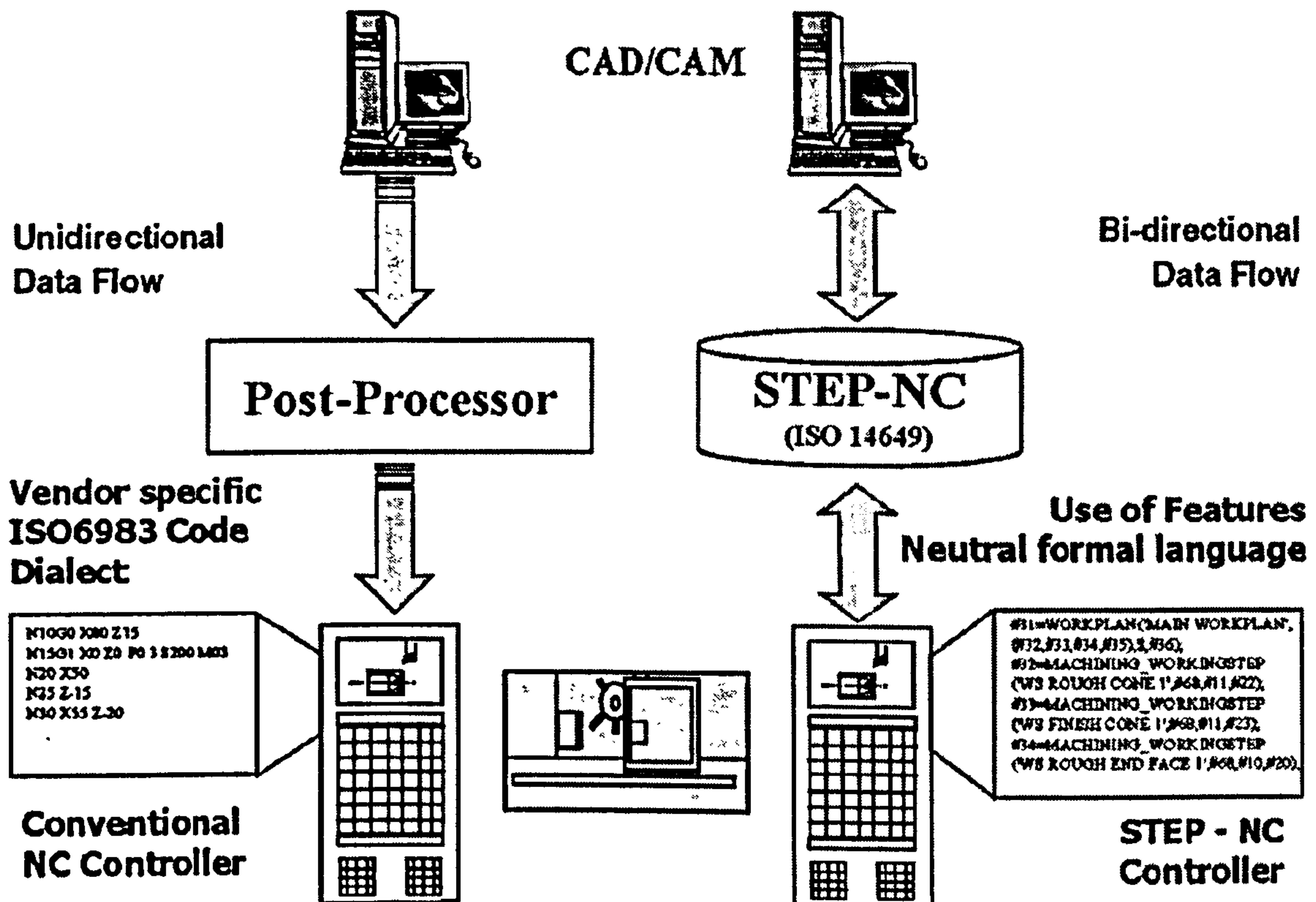


Figure 4.5 Comparison between the current NC interface and the new data interface based on STEP-NC (Rosso Jr *et al.* 2004)

#### 4.5.2 STEP-NC process plan

The STEP-NC process plan is mainly made up of a highly structured *workplan* comprising of a sequence of *workingsteps*. It is presented in a physical file format laid out in the ISO 10303-21 standard, which divides it into 2 sections namely the 'header' and 'data' sections, as shown in figure 4.6. In the header section, the general information relating to the process plan is stated, such as the author, filename and company name. As for the data section, the content is led by the project entity containing the main *workplan* and *executables*, which initiate the actions on a machine tool. The main *workplan* describes a sequence of executable *workingsteps* linking the geometry description, such as the manufacturing features, with the technology description, such as the machining operations, cutting tools, feed rate and setup. Hence, STEP-NC provides the machine tool controller with rich information that can be used for just-in-time tool selection, tool path generation, intelligent error recovery, and other capabilities for intelligent control (Procter *et al.* 2002).

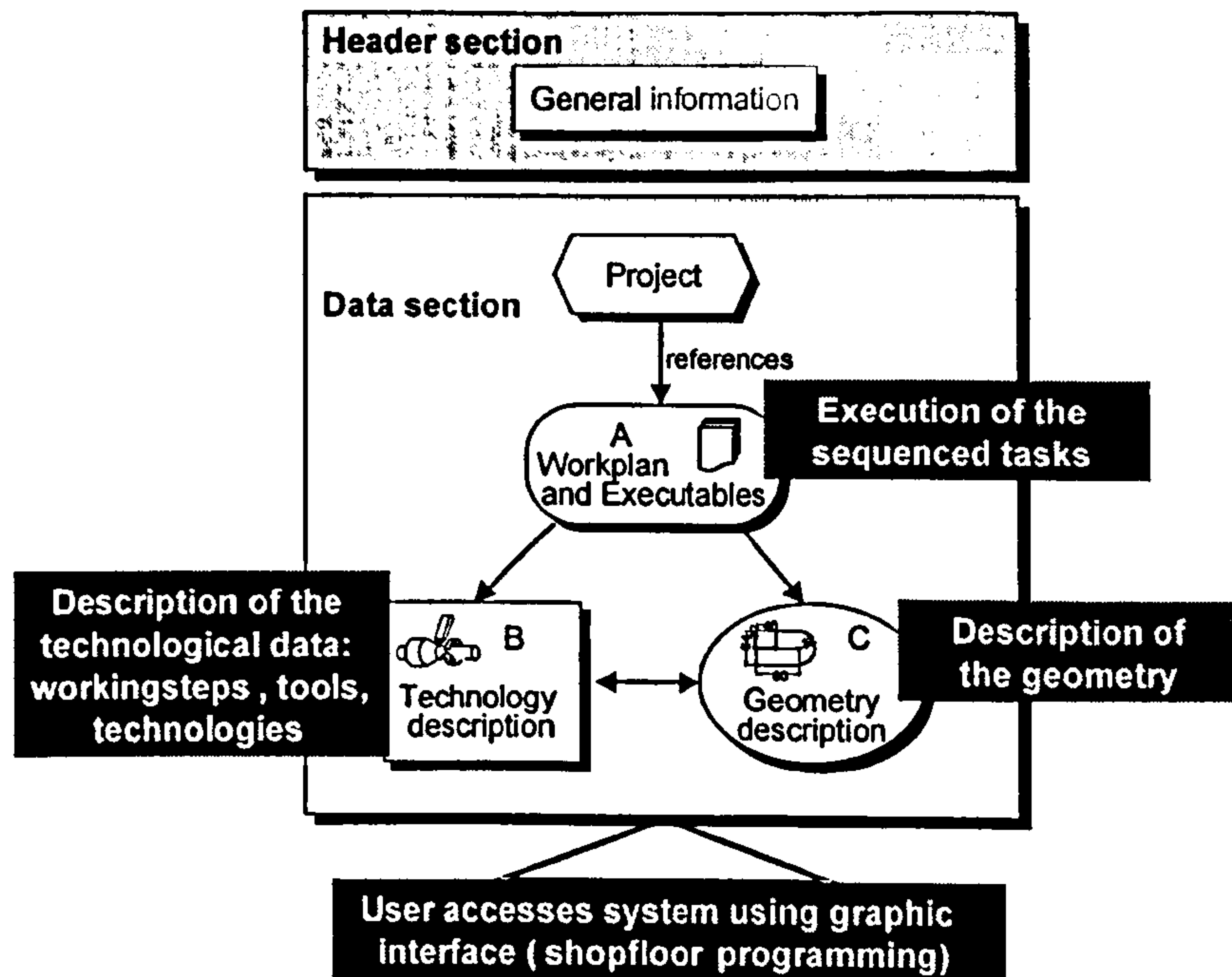


Figure 4.6 Structure of the STEP-NC process plan based on ISO 10303-21 (Xu and He 2004)

#### 4.5.3 STEP-NC data model and data structure

This section examines the 2 versions of implementing STEP-NC developed by the ISO, namely the ISO 14649 (ARM version) and the ISO 10303 AP 238 (AIM version).

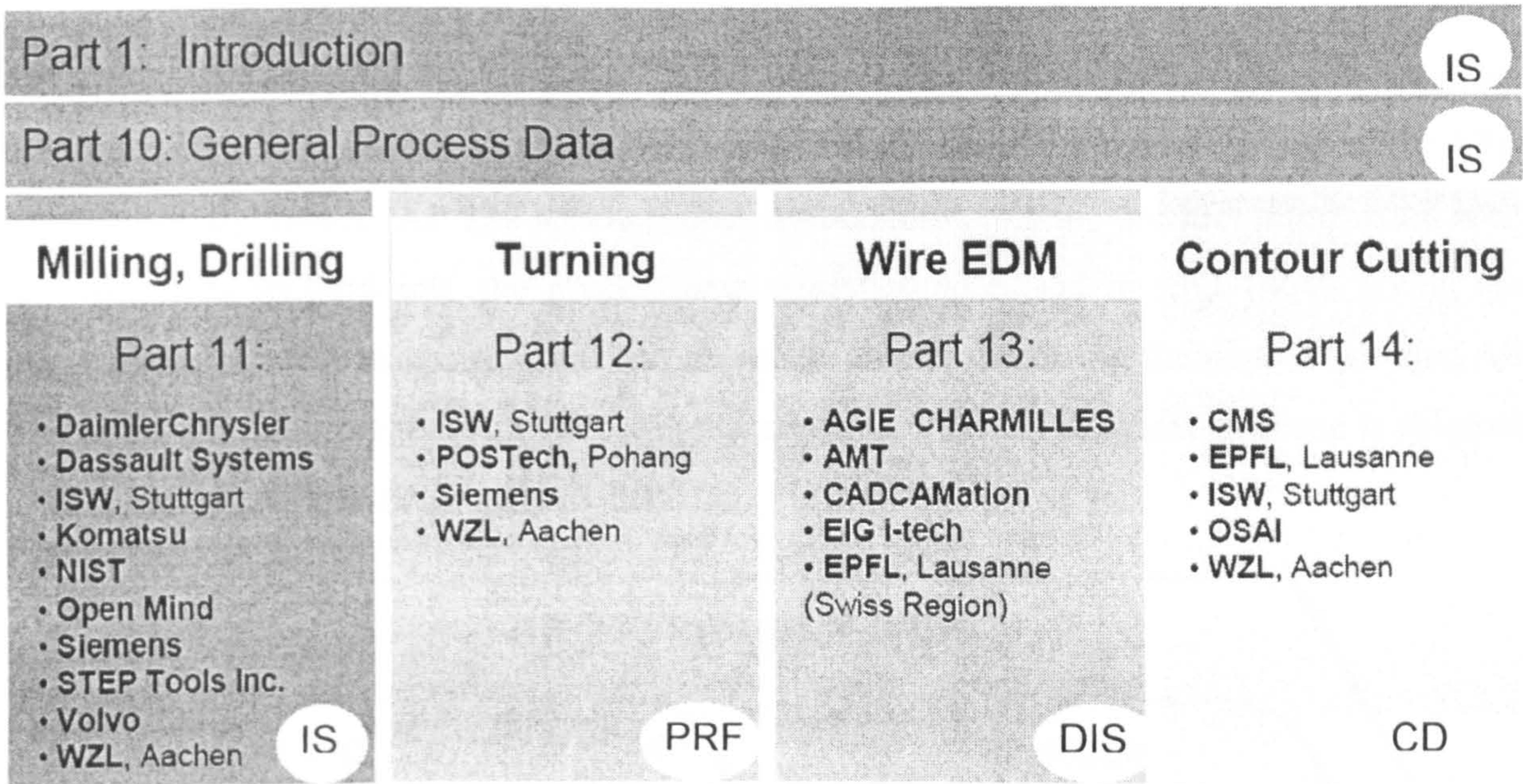
##### 4.5.3.1 ISO 14649 (ARM) for standalone NC implementation

ISO 14649 extends the STEP product data models for CNC machining applications. It uses the EXPRESS language specified in ISO 10303-11 to define the various STEP-NC process data models needed to carry out a CNC machining operation. The ISO 14649 standard mainly concentrates on covering both the general machining data and the process specific data, as shown in figure 4.7. By strictly separating the geometrical, operational and process sequence data, the information access and storage are simplified and exchange between highly specified modules becomes possible (Xu and He 2004). The figure also depicts the various academics and industries who have contributed to the development of the ISO 14649 standard. The various parts of the ISO 14649 standard include:

- ISO 14649-1 (2003) provides an overview and fundamental principles
- ISO 14649-10 (2004) specifies the general process data
- ISO 14649-11 (2004) specifies the process data for milling
- ISO/PRF 14649-12 (2004) specifies the process data for turning
- ISO/DIS 14649-13 (2003) specifies the process data for WEDM
- ISO/CD 14649-14 (2002) specifies the process data EDM



ISO 14649: STEP compliant NC programming interface



IS: International Standard

PRF: Proof of new International Standard

DIS: Draft International Standard

CD: Committee Draft

Figure 4.7 STEP-NC (ISO 14649) architecture (Weck and Wolf 2003)

ISO 14649 aims to model the complete information requirement that must exist in a controller to control a machine tool. In STEP terminology, it is referred to as the ARM that mainly provides the structure of the program execution by specifying a sequence of *workingsteps* with the associated machining process parameters. The general process data model for the machining schema is specified in the ISO 14649-10 standard, which makes references to the process-specific data models defined in different parts of the standard. These process-specific data models contain the relevant data types for a number of processes, such as the basic definition for a milling, turning or WEDM operation. The ISO 14649-10 also includes the definition of the workpiece and a collection of manufacturing features for different processes. However, it has been widely criticised (Feeney *et al.* 2003) for the objective way of presenting the process model without making substantial reference to the product data models. ISO 14649 does not include the geometric items and representations, which are referenced to the ISO 10303's generic resources, in the machining schema (Xu and He 2004). Consequently, the use of AP 238 is considered within the STEP community to pave the way for a full integration of the ISO 14649 standard with the ISO 10303 IRs.



#### 4.5.3.2 ISO 10303 AP 238 (AIM) for STEP integrated CNC

ISO 10303 AP 238 (2004) is the result of further development carried out by the STEP community to harmonise the common field of product data types over the life cycle. It maps the information requirement modelled in the ARM (ISO 14649) onto the various STEP APs, as shown in figure 4.8. AP 238 acts as a data fusion annotating the product information with manufacturing features into the process data model standardised in ISO 14649 giving the machine controller greater intelligent and autonomy in manufacturing the part. Therefore, AP 238 enables a tight integration with the applications that use STEP constructs and is referred to as the AIM in STEP (Procter *et al.* 2002).

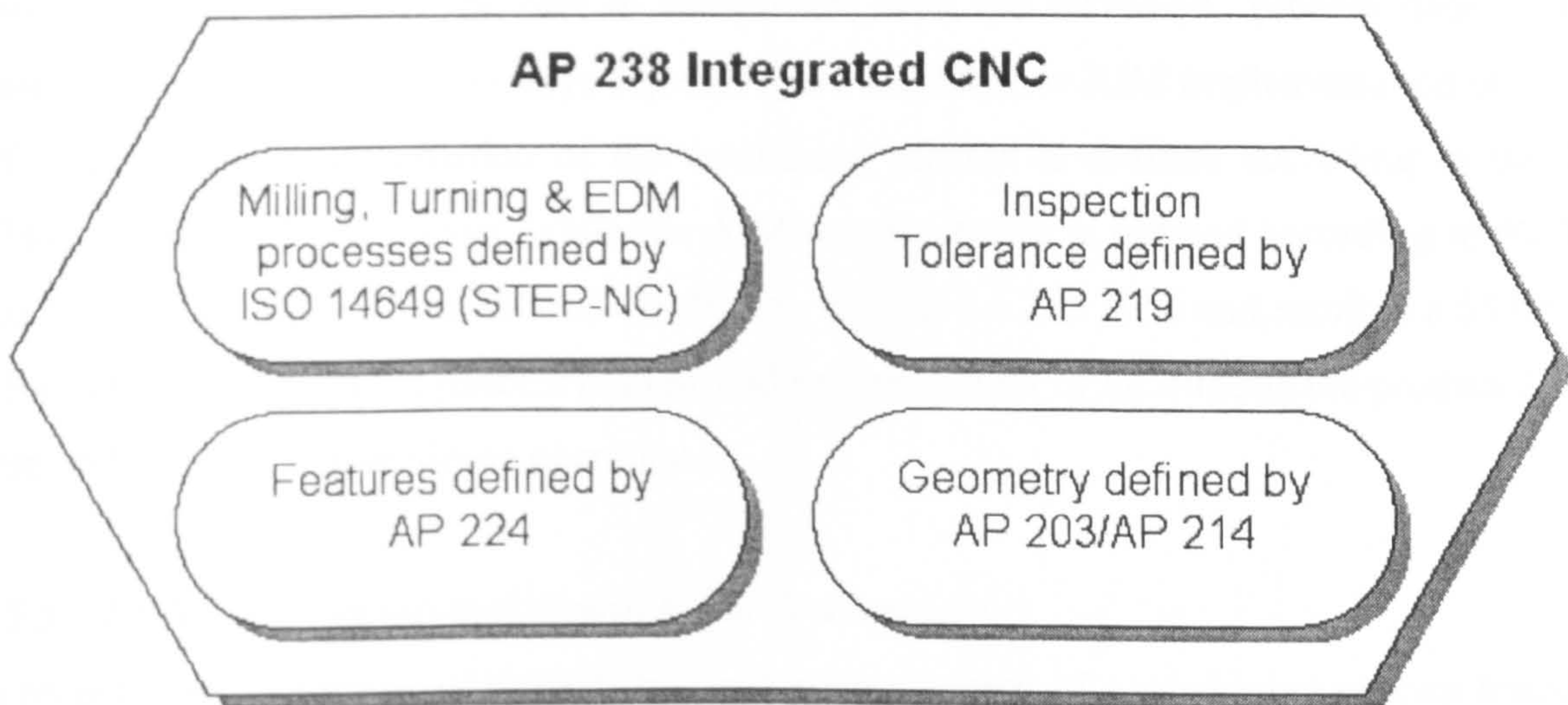


Figure 4.8 AP 238 – STEP integrated version of STEP-NC (Xu and He 2004)

In addition, AP 238 uses the mapped information requirement to obtain the implementation methods allowing the different applications to be supported within one AIM model. It facilitates the feature recognition system to read the CAD geometrical data defined in AP 203 and AP 214, as the manufacturing features specified in AP 238 are harmonised with AP 224. Similarly, the machine probing and inspection systems are able to read the tolerances in AP 238, which matches with those defined in AP 219 and AP 203. Therefore, the AP 238 can replace the ISO 6983 as the new input to CNC by extending a single structured feature-based representation of the product with all the relevant information that a programmer needs to machine a part.

The major difference between the two versions is the degree they use the STEP representation methods and technical architecture (Feeney *et al.* 2003). ARM defines a set of NC domain



requirements models, whereas AIM is the result of implementing the ARM with STEP concepts of using both the IRs and APs. Most of the European work uses the ARM version, which is easier to implement while the US work uses the AIM version, which encompasses a number of AP's (Rosso Jr *et al.* 2004).

#### 4.5.4 *STEP-NC compliant CAD/CAM system*

The external process plan generator exploits the information requirements specified in the various standards to plan the machining process in the form of a STEP-NC compliant CAD/CAM system. It makes use of the STEP product data models defining 'what-to-make' and plans 'how-to-make' the part in compliance with the STEP-NC process data models. This can be carried out in two ways depending on the ARM or AIM implementation of STEP-NC. The ARM representation of the machining schema is defined according to the ISO 10303-21 physical file format, while the AIM representation is defined according to the ISO 10303-22, ISO 10303-27 or ISO 10303-28, see section 4.4.2.2. The end result is a STEP-NC information model-driven process plan providing the context of facilitating the product data to plan and control the machining operation.

#### 4.5.5 *STEP-NC international research and development*

In recent years, a number of projects involving the planning of a machining process based on the STEP-NC data models have been developed and implemented. Table 4.1 shows the participants and the distribution of the technological scope within the IMS project, which has effectively entailed an international research and development into the ISO 14649 standard. The major contribution from the international research institutes and industries include:

##### *i. European STEP-NC research*

A major development from Europe is the STEP-NC compliant Siemens controller based on the company's Sinumeric 840D control working in the milling applications by incorporating it with the Siemens ShopMill shopfloor-oriented NC programming (SFP) system (Hardwick and Loffredo 2001). This enables the STEP-NC physical files to be integrated directly with the controller, with visualisation of the machining features and associated *workingsteps* in the STEP-NC compliant version of their ShopMill CAM system (Rosso Jr *et al.* 2004). Daimler Chrysler and Volvo have commercially demonstrated the capabilities to incorporate the ISO 14649 standard within the CAD/CAM products and export the STEP-NC output to the Siemens 840D control (Weck and Wolf 2003).

Region	EU	Switzerland	Korea	USA
Technologies covered	Milling			
	Turning, Wood/glass cutting, Stone machining, Inspection	Wire/Sink EDM	Turning, Rapid Prototyping, XML - formatted STEP-NC data structure	AIM for Milling & Turning (STIX)
End user	<ul style="list-style-type: none"> <li>• Daimler Chrysler</li> <li>• Volvo</li> <li>• Franci (Italy)</li> <li>• Progetti</li> </ul>	<ul style="list-style-type: none"> <li>• Derendinger</li> <li>• Wyss</li> </ul>	<ul style="list-style-type: none"> <li>• Samsung</li> </ul>	<ul style="list-style-type: none"> <li>• IRB(including</li> <li>• Boeing</li> <li>• Lockheed Martin</li> <li>• General Electric</li> <li>• GDLS</li> <li>• General Motors ...)</li> </ul>
Machine tool manufacturer	<ul style="list-style-type: none"> <li>• CMS (Italy)</li> </ul>	<ul style="list-style-type: none"> <li>• AGIE</li> <li>• Starrag</li> </ul>		
Control manufacturer	<ul style="list-style-type: none"> <li>• Siemens *</li> <li>• OSAI (Italy)</li> <li>• Fidia</li> </ul>			
CAM manufacturer	<ul style="list-style-type: none"> <li>• Open Mind</li> <li>• Dassault</li> </ul>	<ul style="list-style-type: none"> <li>• CADCAMation*</li> </ul>	<ul style="list-style-type: none"> <li>• Cubictek</li> </ul>	<ul style="list-style-type: none"> <li>• STEP Tools</li> <li>• Gibbs &amp; Associate</li> <li>• BA Solutions</li> <li>• Numerical Control Services</li> </ul>
Research institute	<ul style="list-style-type: none"> <li>• WZL (RWTH AACHEN)</li> <li>• ISW (University of Stuttgart)</li> <li>• KTH</li> </ul>	<ul style="list-style-type: none"> <li>• EPFL</li> <li>• EIG I-tech</li> </ul>	<ul style="list-style-type: none"> <li>• ERC-ACI *</li> <li>• KIST</li> <li>• NRL-SNT</li> </ul>	<ul style="list-style-type: none"> <li>• Louisiana Center for Manufacturing Sciences</li> <li>• Lawrence Livermore National Laboratories</li> </ul>
Association	<ul style="list-style-type: none"> <li>• CECIMO (Belgium)</li> </ul>	<ul style="list-style-type: none"> <li>• AMT</li> </ul>		<ul style="list-style-type: none"> <li>• NIST</li> <li>• Department of Energy</li> <li>• Army's National Automotive Center (NAC)</li> </ul>

Table 4.1 The IMS STEP-NC project partners (Xu and He 2004)

### ii. Korean STEP-NC research

The work in Korea has been developed at the National Research Laboratory for STEP-NC Technology (NRL-SNT) in a close collaboration with Pohang University of Science and Technology. It involved the development of a conceptual framework for an autonomous STEP-compliant CNC taking the data defined in ISO 14649 as an input and carrying out



manufacturing tasks based on a 'process sequence graph' (Suh *et al.* 2002). The process sequence graph is a graphical representation of the sequence of *workingsteps* described in terms of the *machining\_features* and *machining\_operations* using AND-OR relationships. Suh *et al.* (2003) also presented a STEP-compliant CNC architecture for a SFP system consisting of STEP physical file interpretation, feature recognition, process planning, part program generation and verification.

### iii. Swiss STEP-NC research

The Swiss research institutes, namely EPFL (Federal Institute of Technology in Lausanne) and EIG (School of Engineers de Genève at University of Geneva), together with AMT Consulting led the development of the ISO 14649 data model for wire-cut and die-sink EDM in collaboration with machine manufacturer; Agie-Charmilles, CAM manufacturer; CADCamation and machine tool user; Wyss SA (Nguyen and Stroud 2003). They proposed a data model that was capable of storing information necessary for the input and output of the proprietary expert system for the WEDM process (Kiritsis 2001), as illustrated in figure 4.9. The expert system is commonly used in the WEDM CAD to CNC process chain and has complicated the standardisation of the data structure toward an integrated manufacturing environment.

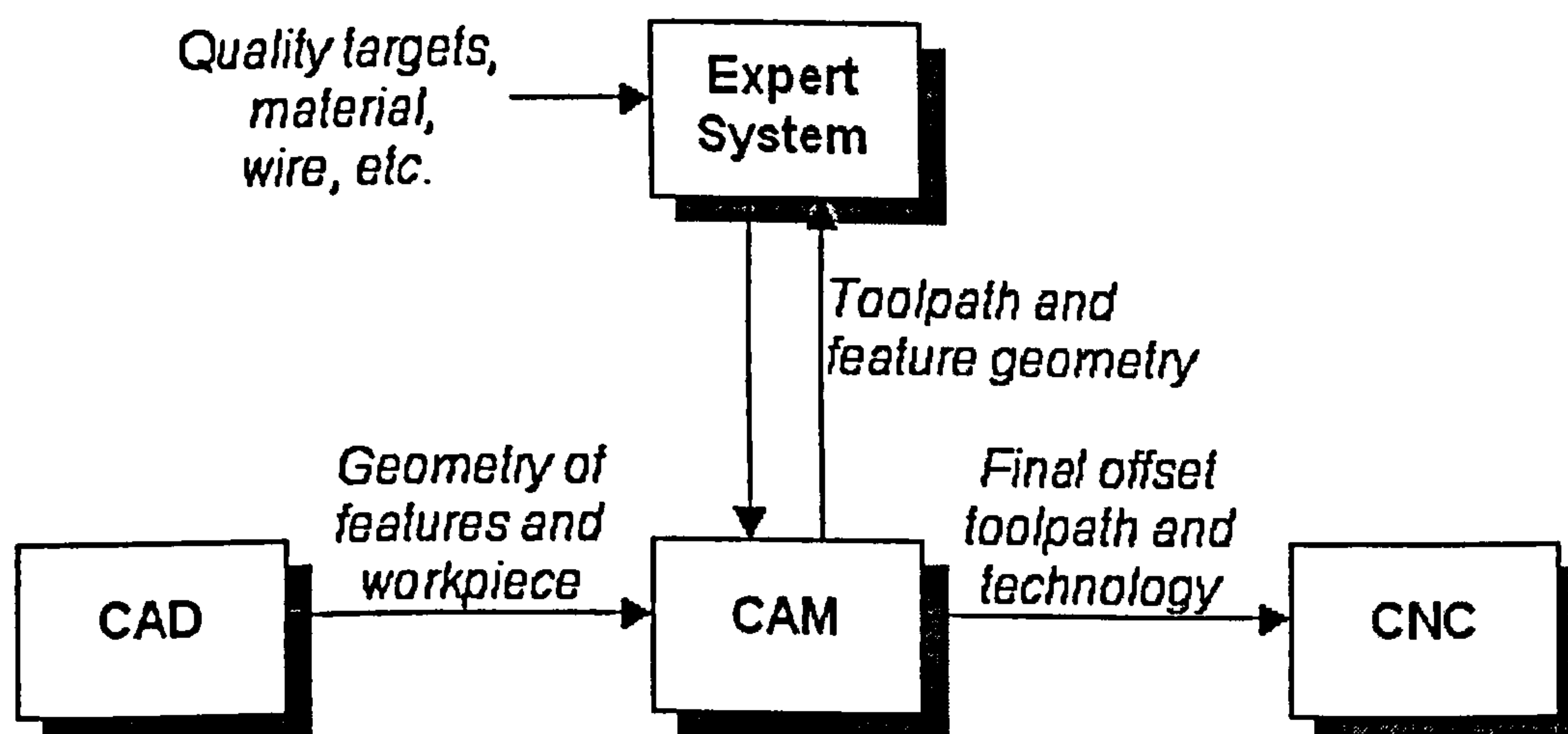


Figure 4.9 WEDM CAD-CAM-CNC process chain (Kiritsis 2001)

In addition, these partners are also responsible for developing and finalising the concepts and algorithms for the implementation of advanced functions for intelligent WEDM CAM/SFP systems and for the feedback of modified NC programs and its version history (Nguyen and Stroud 2003). The advanced functions include computing the wire trajectory based on the

ruled surface and checking the collision between the wire and the adjacent surfaces when cutting features with sharp corners. Richard *et al.* (2004) have successfully demonstrated the 3D offset compensation on the ruled surface features for the WEDM process.

#### *iv. US STEP-NC research*

The STEP-NC project in the USA termed Super Model led by STEP Tools Inc. (2005) has made a significant contribution to the automation of the CAD to CNC manufacturing process through the use of STEP. Super Model aims to support a three-stage design process, namely functional design, manufacturing design and process design, and deliver the data produced by the process to an intelligent controller generating the cutting toolpath from the STEP-NC data (Hardwick and Loffredo 2001), as shown in figure 4.10. One of the most exemplary demonstrations mainly involved the use of the GibbsCAM programming system to facilitate:

- a. Reading the demonstration part defined in AP 203 format through the use of the GibbsCAM STEP Translator. The part was then programmed by using GibbsCAM's graphical interface, and visually verified by using its cut part rendering capability (Albert 2005).
- b. Reading the demonstration part defined in AP 238 format and downloading it from the Internet through the use of the GibbsCAM STEP-NC adaptor plug-in. The STEP-NC adaptor then produced the GibbsCAM tooling, process and geometry elements and executed GibbsCAM functions to generate the toolpath corresponding to the AP 238 manufacturing features without any operator invention (Xu and He 2004). Subsequently, the part was machined on a retrofitted three-axis Bridgeport vertical milling machine, which was controlled by a STEP-NC controller comprising of an MDSI (Manufacturing Data System, Inc.) soft controller running on a PC-based NT platform (Lewis 2002). The MDSI soft controller is an open PC-based CNC software, which eliminates the need for intelligent board-level controller cards or other proprietary hardware.
- c. Integration with an open modular architecture controller (OMAC) through the use of the AP 238 process plan, resulting in a two-way interface between the CAM and NC control systems (Waurzyniak 2001). As in the previous demonstration, the AP 238 data file provided all the manufacturing information enabling the automation of CAM processing and cutting toolpath generation to be carried out on GibbsCAM. The machining



demonstration was performed on a three-axis horizontal milling machine on a wax version of a typical part.

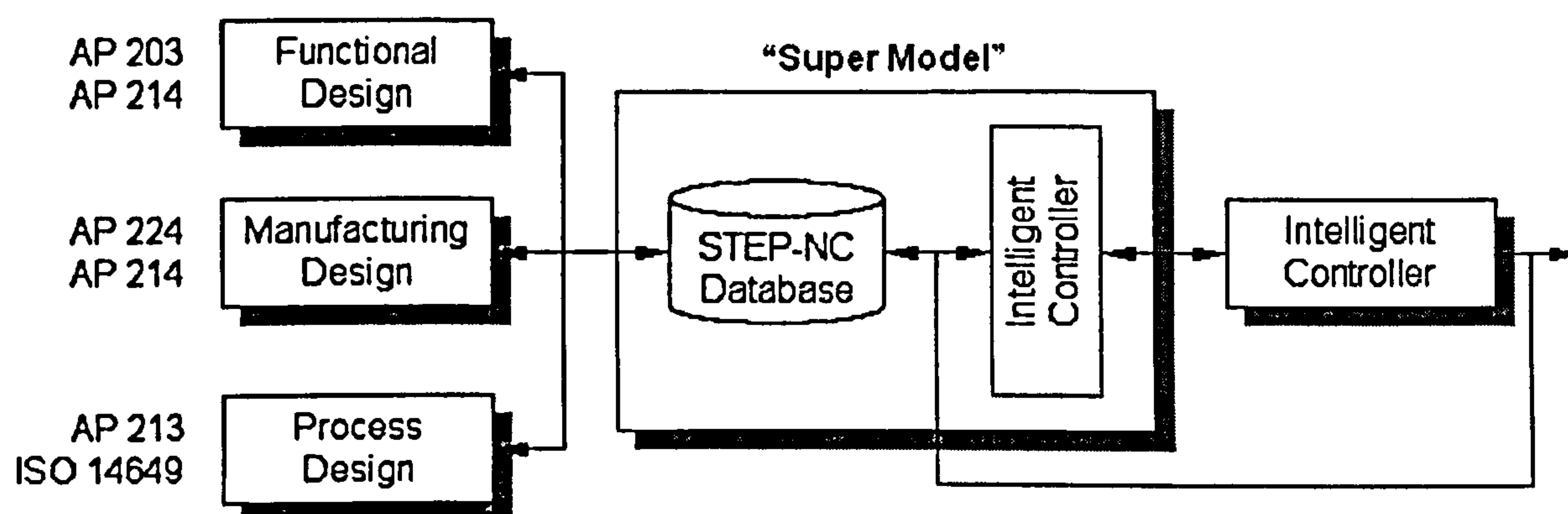


Figure 4.10 STEP Tool Inc. Super Model project (Hardwick and Loffredo 2001)

#### v. STEP-NC research at Loughborough University (UK)

The research work from Loughborough University has mainly concentrated on the planning of the machining process and the generation of the STEP-NC process plan for milling and milling/turning components. Allen *et al.* (2005) developed a STEP-NC compliant computational environment for a multi-agent framework, where agents represented the individual features of the component and work independently and cooperatively to generate STEP-NC process plans for discrete component manufacture. Rosso Jr. *et al.* (2004) discussed the need for a new ISO 14649 machining schema specifically for asymmetric rotational parts and outlined a feasible solution to use the ISO 14649 data model for turn/mill machining. Further work was undertaken by Ali *et al.* (2005), who designed and implemented a STEP compliant inspection framework providing a capability to establish standardised measuring and inspection across the total CAx chain.

## 4.6 Critique

This section critiques the evolution of the STEP-NC in terms of the pioneering product definition standards and the NC machining process planning development.

### 4.6.1 Product definition standards

The pioneering product definition standards such as IGES, PDDI and PDES, are still widely adopted by today's CAD industry despite of their ambiguities in certain areas. IGES has been a dominant standard for CAD data exchange since its inception in the early 1980s. Its most exemplary characteristic is the ability to exchange data among different CAD systems that

translate IGES files into their proprietary format. However, IGES does not have a formal information model that captures the essential manufacturing information to fulfil the needs of CAM applications. On the other hand, PDDI was initiated in the mid 1980s to improve the underlying principles of IGES, which then led on to the development of PDES in the late 1980s. Although PDES captures the complete information about a product and provides the physical mechanism for data exchange, it gives no onus to the vendors implementing specific entities to suit their own application. These deficiencies in IGES and similar formats led to the twin requirements of a formal definition language and conformance requirements, both of which are leading-edge technologies (Bloor and Owen 1991).

STEP attempts to unite the various efforts of developing an agreed international standard and to surpass all its predecessors' scope and infrastructure. Its information model covers not only geometry but also deals with topology, features, tolerances and materials. Its information structure is designed to be modular and extensible but is constrained by the relationships between the entities. In addition, STEP ensures that implementation is conformed to a particular application domain through the use of conformance testing. Unlike the other standardisation activities, STEP is forward looking, and a number of experimental product modelling systems have been developed based upon the STEP standard and commercial system interpreters (Dutta *et al.* 1998). Most CAD software vendors have been equipped in their new releases with a STEP data translator, such as AutoCAD (Autodesk 2005) and Solid Edge (UGS 2005).

#### 4.6.2 NC machining process planning

Most of today's CNC machines are still programmed in the G & M code language. The part program is generated by the CAM system, which makes use of the geometric information residing in the CAD system, to code the sequences of axis motions and tool functions. However, the data interoperability problem surfaces when building an environment for CAD/CAM system users on different sites, which requires a good communication tool and a proper standard to represent all the information to be transferred (Chao and Wang 2001). Such a problem prompted the need to develop a new data interface fusing the design and manufacturing intent together, and to look beyond the current range of information giving the CNC greater control and intelligence to machine a component. Against this backdrop, STEP Tools Inc. (2005) spearheaded the Super Model project in the US generating huge academia and industrial interests in solving the data interoperability problem in manufacturing. The



Super Model project is in effect a STEP model-driven intelligent control of manufacturing, which seeks to develop software and databases for an integrated design-to-manufacturing system allowing product design data to control CNC machine tools (Hardwick and Loffredo 2001).

STEP-NC aims to provide the complete information requirements that must exist in the machine tool controller. The information requirements include part geometry, manufacturing feature and manufacturing processes covering the need of the applications and tasks that a part programmer performs. Instead of programming the cutting toolpath and machine tool functions, STEP-NC describes the various *machining\_workingsteps* required to machine a specific STEP manufacturing feature. Therefore, STEP-NC has effectively replaced the part programmer by defining the manufacturing features to be machined and associating essential manufacturing information, such as the machining process parameters with the feature. STEP-NC is becoming increasingly popular over the legacy format of the G & M codes within the research community contributing to the future global manufacturing needs.

With the widespread use of the Internet, the networking of CAD/CAM systems across the globe will become increasingly apparent in the manufacturing industries. Through the use of STEP-NC and web-based technologies, resources can be easily accessed and work can be readily exchanged, thereby lowering the cost and leadtime of a project. Moreover, integrating procurement, design and manufacturing together within an e-manufacturing system promises to help give manufacturers the ability to eliminate product design changes far upstream, where such changes have the greatest negative impact on costs (Waurzyniak 2001). General Dynamics Land Systems (GDLS) has successfully integrated GibbsCAM and OMAC demonstration machining of a part from a STEP-NC part program downloaded from the Internet using XML (Hardwick and Loffredo 2001), thus overcoming the interoperability problems posed by disparate CAx and CNC systems in manufacturing. Though significant research and development have successfully demonstrated the benefits and potentials of STEP-NC, it still requires continual expansion with different parts issued to a wider variety of product types and life-cycle stages before it can be accepted as a discrete manufacturing approach when dealing with far-flung suppliers/facilities across the globe.

## Chapter 5

# DESIGN OF AN INTEROPERABLE STEP-NC COMPLIANT WEDM CAX SYSTEM FRAMEWORK

### 5.1 Introduction

This chapter proposes the research framework for a STEP-NC compliant WEDM CAX system based on the author's WEDM information models designed from the STEP-NC standards. The framework is described by mainly exploring the information and functional perspectives of the CAX to CNC process chain. These perceptions represent the author's view and are described in the first part of the chapter. The major part of the chapter discusses the use of the system framework within an interoperable manufacturing environment. The information models required to drive the system are discussed in depth in the following chapter 6.

### 5.2 Fundamentals of machining process planning

The fundamentals of planning a machining process by examining the representation of information and through the generation of a process plan is of critical importance. The information representation is described in terms of modelling the information whereas the process plan generation is described in terms of the approaches of manipulating the information supporting the machining process.

#### 5.2.1 *Representation of product and manufacturing information*

The essential information supporting manufacturing decision-making can be represented as a product model (PModel) and a manufacturing model (MModel). The PModel captures the information related to a product throughout its life cycle, whereas the MModel captures the information about the manufacturing situation of a company in terms of its manufacturing facility and capabilities (Molina and Bell 1999). These information models, which have been well-established by several authors (Molina *et al.* 1995, Molina and Bell 1999), are equally important and need to be highly integrated. The information held within the MModel allows the product designer to study the effects of machining operations, machines, tools, fixtures/jigs, operation sequence, and machining parameters at an early stage of product development. Similarly, the information held in the PModel allows the manufacturing



process planner to manufacture the product according to the required geometry and tolerances.

The role of integrating the different computer environments supporting these product design and manufacturing process activities is played by a computer-aided process planning (CAPP) system. Previously, much of the information modelling research, particularly in manufacturing information modelling has been developed based on the viewpoint of the individual researcher and has not concentrated on information standards. This requirement has been recognised by the author and through the use of the STEP-NC standard such generic models have been developed as described in section 5.3.1.

### 5.2.2 *Planning of machining process*

Process planning has been defined by Alting and Zhang (1989) as a function within the manufacturing environment which deals with selecting the manufacturing processes and parameters to be used to transform a part from its initial form to final shape according to design specifications. To achieve this, it requires a part representation containing sufficient information for the properties to be evaluated, and a reasoning scheme in a form of rules and algorithms that carry out evaluation using the part representation (McMahon *et al.* 1997). The different approaches to machining process planning have been classified by Ham and Lu (1988) as variant, semi-generative and generative approaches. The variant approach involves retrieval and modification of a previous process plan to reflect the characteristics of the part, whereas the generative approach produces a completely new process plan for the part. The latter approach may utilise the decision table, decision trees or AI (artificial intelligence) techniques to develop a knowledge-based process planning system (Sormaz and Khoshnevis 1997). As for the semi-generative approach, it is a cross-breed incorporating both the quasi-variant and quasi-generative features.

Thus, the accuracy of process planning is dependent not only on the content of the information requirement but also on the manipulation of the information in order to produce a detailed description of the manufacturing operation sequences required to machine a part. A major contribution of this research is identifying a system framework that generates a STEP-NC process plan for WEDM component manufacturing based on the essential information requirement and the basic WEDM process logic and rules needed to plan the machining process.

### 5.3 STEP-NC compliant WEDM CAx system framework

This section proposes a system framework for a STEP-NC compliant WEDM CAx to CNC process chain by taking both information and functional perspectives of the system. The information perspective of the system framework is explained in terms of the information models and the data models needed to drive the WEDM CAx system. As for the functional perspective, it provides the methodology of planning the process and generating the process plan for WEDM component manufacturing.

#### 5.3.1 Information perspective of system framework

The system framework has relied on the information models, namely the PModel and the MModel, to satisfy the information requirement of planning and generating a process plan for the WEDM process. The PModel defines all the product-related information encountered during its life cycle, such as the descriptions of billet, the design of product together with the manufacturing view of the product. The manufacturing view provides a link between the PModel and MModel, and only has specific instances of the manufacturing processes (Liu and Young 2004). Whereas in the MModel, it identifies and represents the information relating to the manufacturing resource, manufacturing process and manufacturing strategy. The latter represents how the resource and process are organized, composed and deployed to support the realization of the manufacturing function (Molina and Bell 1999). Thus, the PModel and MModel capture the complete information and knowledge required to carry out the WEDM process.

The data models for WEDM component manufacturing have been based on the ISO 14649 standard, which is made up of different explicit parts providing the general and specific process data. Part 10 is the backbone of the standard covering the common data structures for most machining processes, see section 4.5.3.1. These data structures describe the part to machine and the task to perform. In the standard, the part is defined as a *workpiece* while the task is defined as a *workplan* consisting of a series of *machining\_workingsteps* to carry out the *machining\_operation* on a *manufacturing\_feature*. On the other hand, the subsequent parts of the standard contain the data structures for a particular machining process, such as the ISO/DIS 14649 part 13, which is dedicated to the WEDM process, see section 4.5.3.1.

The ISO/DIS 14649-13 data structures are extended from those defined in part 10 and provide the descriptions of the *wire\_edm\_machining\_operation* used in the WEDM process. Figure



5.1 shows the author's overall STEP-NC compliant data structure whose root is defined as a *project*. The *project* thus describes the *workpiece* to be manufactured in terms of *material*, *global\_tolerances*, *geometry* and *boundary\_geometry\_select*, and the *workplan* to be performed in terms of the *setup* and *machining\_workingstep*.

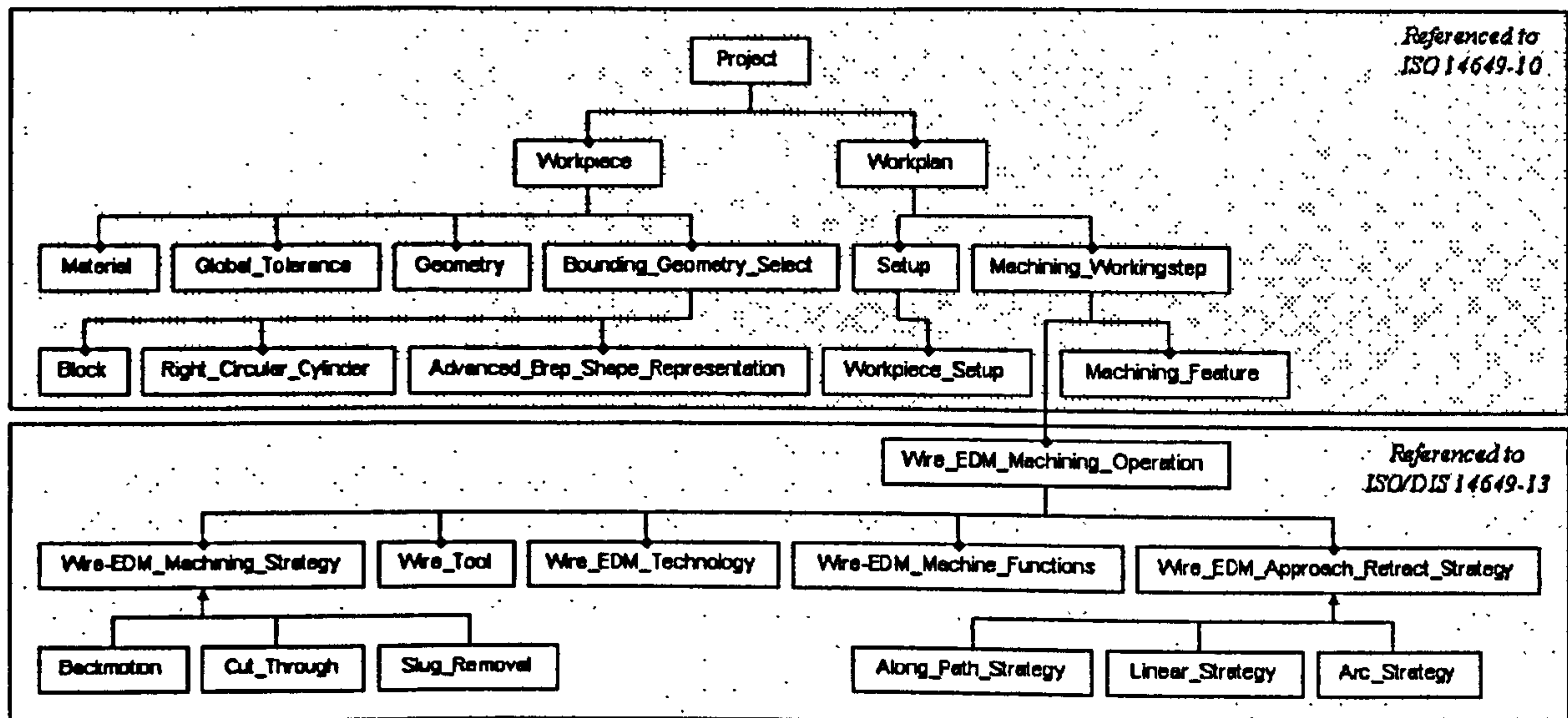


Figure 5.1 WEDM data model based on ISO 14649 standard

### 5.3.2 Functional perspective of system framework

The system framework exploits the information and knowledge existing in the PModel and MModel to support STEP-NC compliant planning of the WEDM process. It has been designed to be a semi-generative process planning system, which enables the interoperable manufacturing of a product at a different location/company by a different WEDM machine with dissimilar manufacturing process capability. Figure 5.2 shows the system framework depicting the STEP-NC compliant information models and the operational structure of the process plan generator. The term interoperability is used in this research to refer to the ability of the STEP-NC process plan generated from the system framework to operate among the different software systems in the CAx to CNC process chain, thereby promoting the ease of exchanging the information and knowledge about the WEDM process.

The operational structure of the generator has been aligned with the use of PModel and MModel spelling out the design and manufacturing intent of the part. It is made up of three major stages namely the translation of the geometrical features, the planning of the machining operation and the generation of the process plan. The machining operation planning stage is

sub-divided into 3 stages, which define the WEDM constraints, identify the WEDM capability and determine the WEDM schema.

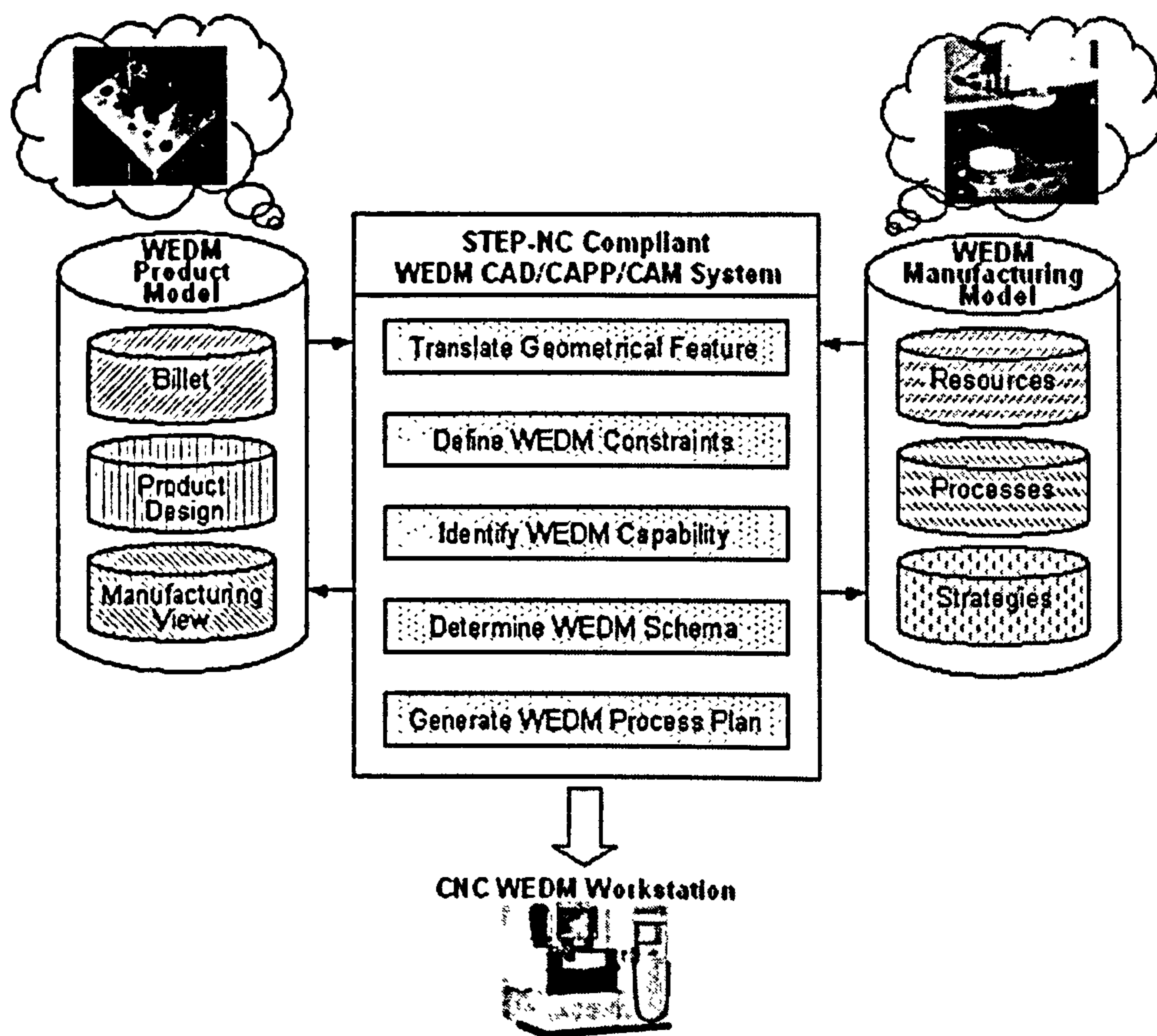


Figure 5.2 System framework for STEP-NC compliant WEDM CAX system (Ho *et al.* 2005)

However, if integration and automation are to be achieved in the CAPP system, a logical approach to the identification of a planning structure is needed (Ham and Lu 1988). This has been realised by identifying the essential planning activities and their relationships through the use of the IDEF0 activity modelling methodology. IDEF0 stands for ICAM Definition level 0 (Colquhoun *et al.* 1993) and provides a valuable representation of activity relationships and information flows illustrated as an abstract at the top level to the detail at the bottom level. Figure 5.3 shows the IDEF0 representation of the proposed system at the highest level. Each activity is controlled by a specific part of the STEP and STEP-NC standard together with libraries of manufacturing resources related information, which are briefly described below:

- AP 203/214 specifies the geometry of product,
- AP 219 is used for inspection data and results,
- AP 224 specifies the definition of feature-based component model,
- AP 240 is used in process planning,



- ISO 10303-21 describes the format of the physical file,
- ISO 10303-22 is the SDAI for computing languages such as C++ and Java,
- ISO 14649-10 specifies the general process data,
- ISO/DIS 14649-13 specifies the process data related to WEDM process,
- Fixture library provides information on the jig/fixtures, and
- Machine tool library provides information on the machine tool such as the machine tool specification.

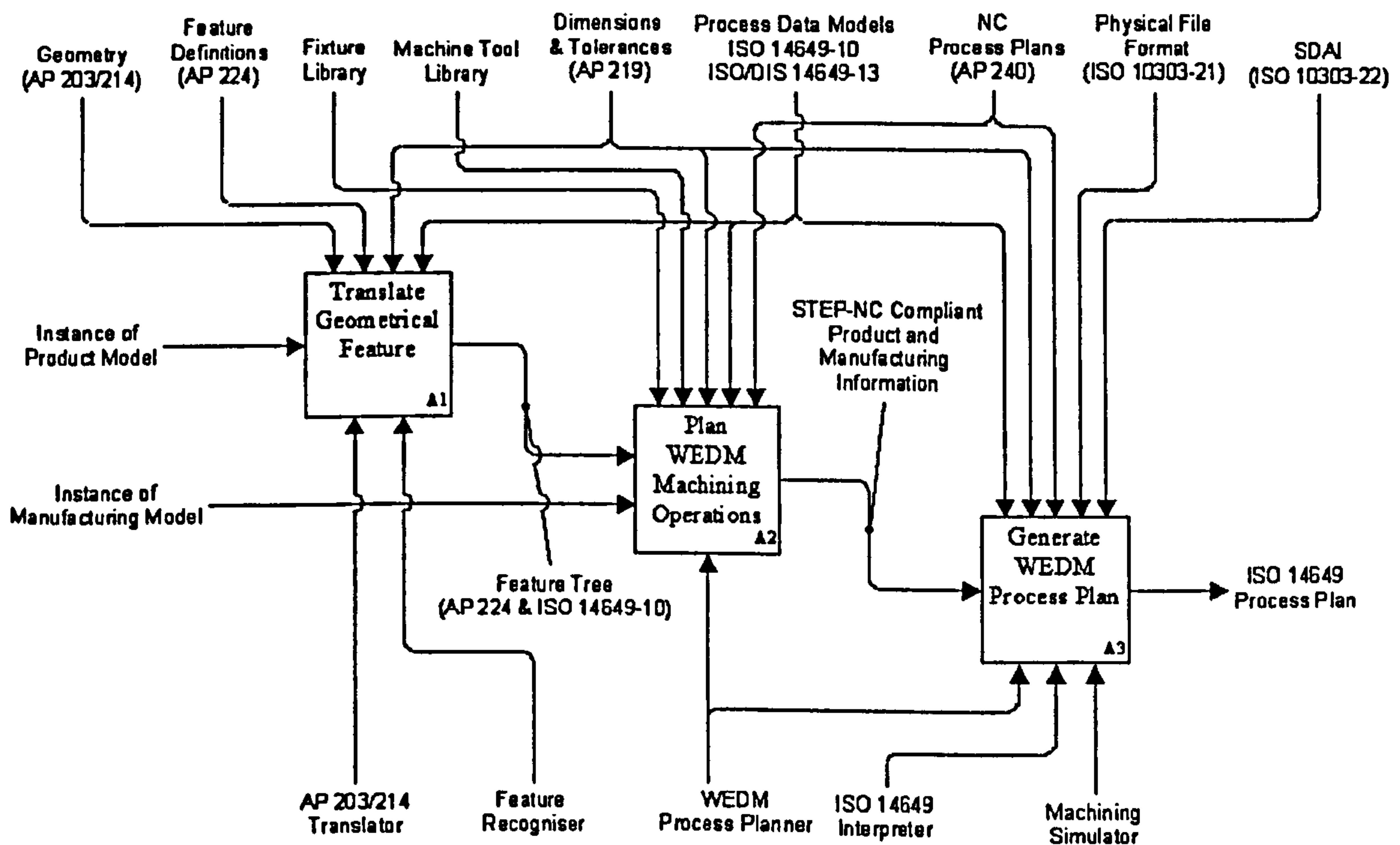


Figure 5.3 IDEF0 representation of the STEP-NC compliant WEDM CAX system framework

## 5.4 Major activities of system framework

The major activities of the proposed system framework for a STEP-NC compliant WEDM CAX system include the translation of the geometrical features, the planning of machining operation and the generation of the STEP-NC process plan. These WEDM process planning activities are outlined below.

### 5.4.1 Feature translation

During the first stage, feature technology has been employed to translate the instance of the PModel for use in applications following design such as machining process planning. It involves the translation of low-level information into a feature-based component model, which has also been used to integrate and automate design and manufacturing applications.

Generally, there are two approaches of translation, namely feature-based design, which uses predefined and application specific features to model a product, and feature recognition, which converts the CAD product model into the feature-based component model without limitations on designer activities (Ozturk and Ozturk 2001). In the proposed system, the author favours the latter approach because it will not restrict the modelling of a product to a limited number of predefined features. It uses a feature recogniser based on AP 224 to extract manufacturing features and relationships, and identifies the required machining operations to machine the part but this is not the core aim of this research. The system also required a translator based on AP 203/214 to interpret the geometry of part. However, Allen *et al.* (2003) believed that the AP224 translator could be further developed to capture the feature information from a feature-based CAD model.

#### 5.4.2 WEDM machining operation planning

The second stage of planning the process has been divided into 3 sub-stages consisting of defining the machining constraints, identifying the machining capability and determining the machining schema. These activities have been designed to capture, organise and use the product and process knowledge via the proposed system to plan a detailed machining operation for the WEDM process. In this research, process planning refers to the making of a plan, which describes the required procedures of conducting a WEDM process, such as the setting up of the workpiece and the identification of the WEDM machining operation for a specific feature-based component. On the other hand, operation planning refers to the making of a plan, which indicates the detailed sequences of the WEDM machining operation, including the machining strategy to employ, the wire tool to use, the cutting conditions to apply, etc. Figure 5.4 shows the machining operation planning activities for the proposed system, which has been largely based on the WEDM MModel and are described as follows:

WEDM resources – define the physical constraints imposed on the WEDM process, e.g. *wire\_tool*, *wire\_edm\_machine\_functions*.

WEDM processes – identify the functional capabilities of WEDM process, e.g. *workpiece\_setup*, *wire\_edm\_machining\_operations*.

WEDM strategies – determine the machining schemas of the WEDM process, e.g. *wire\_edm\_approach/retract\_strategy*, *wire\_edm\_technology*.



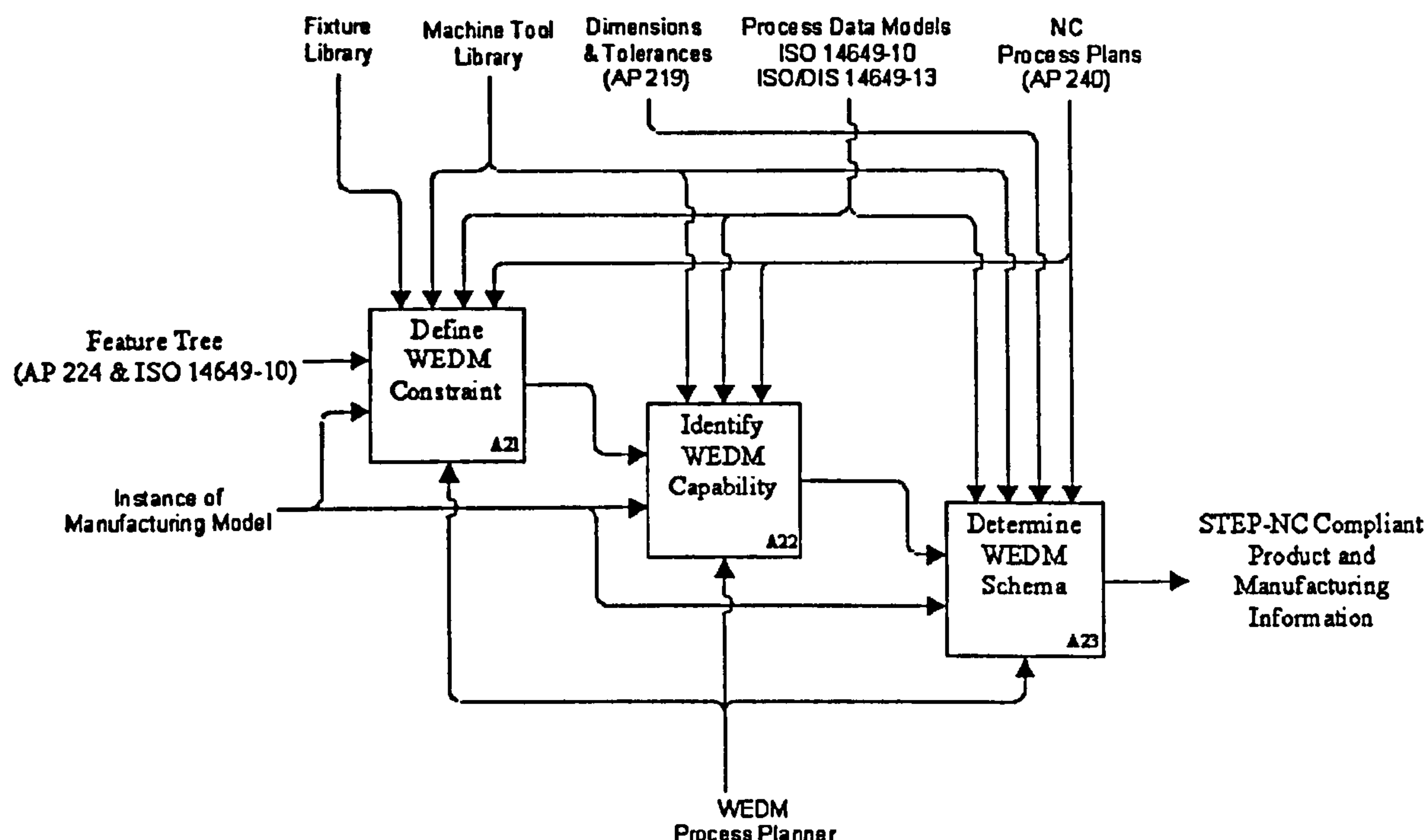


Figure 5.4 IDEF0 representation of WEDM machining operation planning activities

### 5.4.3 WEDM process plan generation

Lastly, the expected output from the system is a STEP-NC compliant and information model driven process plan defining ‘what-to-make’ according to the PModel and ‘how-to-make’ it by conforming to the MModel. The process plan is made up of one top-level entity called *project*, which indicates a machining *workplan* and a *workpiece* upon which manufacturing functions are to be performed. The latter entity contains the characteristics of the workpiece to be machined, such as material, shape and size. As for the *workplan*, it contains a description of setting up the workpiece at the machine tool and a set of sequential *machining\_workingsteps*. Here, each *machining\_workingstep* defines a *wire\_edm\_machining\_operation*, which is based on the machine, tooling and technological capabilities of the WEDM process. The process plan also captures the essential machine dependent information needed to operate the proprietary expert system, which is commonly found in the WEDM process, such as the *wire\_edm\_machining\_strategy*, *wire\_tool*, *wire\_edm\_technology*, etc. The end result is a STEP-NC compliant process plan that is not dependent on the machine tool, thereby providing the capability to operate a WEDM process in an interoperable manufacturing environment.

## 5.5 Interoperable manufacturing environment

An interoperable manufacturing environment has provided the vital means of communicating with or exchanging data between different CAD, CAM and CNC systems. It provides the integrated infrastructures which via computational mechanisms support interaction between business and manufacturing components where potentially such components may be distributed around the factory, globe or even universe (Weston 1998). The five basic approaches identified by Potter (2000) to interoperate one system's CAD data in other applications include the use of a standard neutral file format, direct translators, geometry kernels, CAD program's application programming interface (API) and visualisation technology based on tessellation. In addition, the Microsoft's Object Linking and Embedding (OLE) technology is another method of facilitating interoperability, which enables a product designer to essentially 'cut and paste' a solid-modelling component from one CAD application into another (Rowell 1997). Other options that support the concept of interoperability include programming languages such as Java and Corba. More importantly, the system's interoperability also depends on the industry-wide collaboration between CAD, CAM and CNC vendors sharing data throughout the design through manufacturing cycle.

The proposed system framework supports data interoperability between the various CAX systems or CNCs in the manufacturing chain. Figure 5.5 illustrates how the proposed system operates in an interoperable manufacturing environment. The output from the system is a process plan that is interoperable with the corresponding CAX systems or CNCs. This has been largely made possible by the information models identifying machine independent information that can be executed on the various types of WEDM machine. However, the author believes that a certain level of detail is still needed to be fed into the system due to the proprietary characteristics of the CNCs for the WEDM process. For example, a component that requires four cutting operations at one machine may only need three cutting operations if it was manufactured at another machine to obtain the same surface finish. Such a difference in the machining strategies is determined by the individual CNC vendor's proprietary expert system, which makes it difficult to represent the information and knowledge needed to drive it. As mentioned in section 4.5.5, the expert system is commonly used in the WEDM CAX to CNC process chain to interpolate the cutting contour, monitor and control the machining condition. Hence, it is important that the WEDM process plan contains enough data to allow the CNC to intelligently process or interoperate from machine to machine. This can be



achieved through the information modelling of the manufacturing capabilities of the WEDM process.

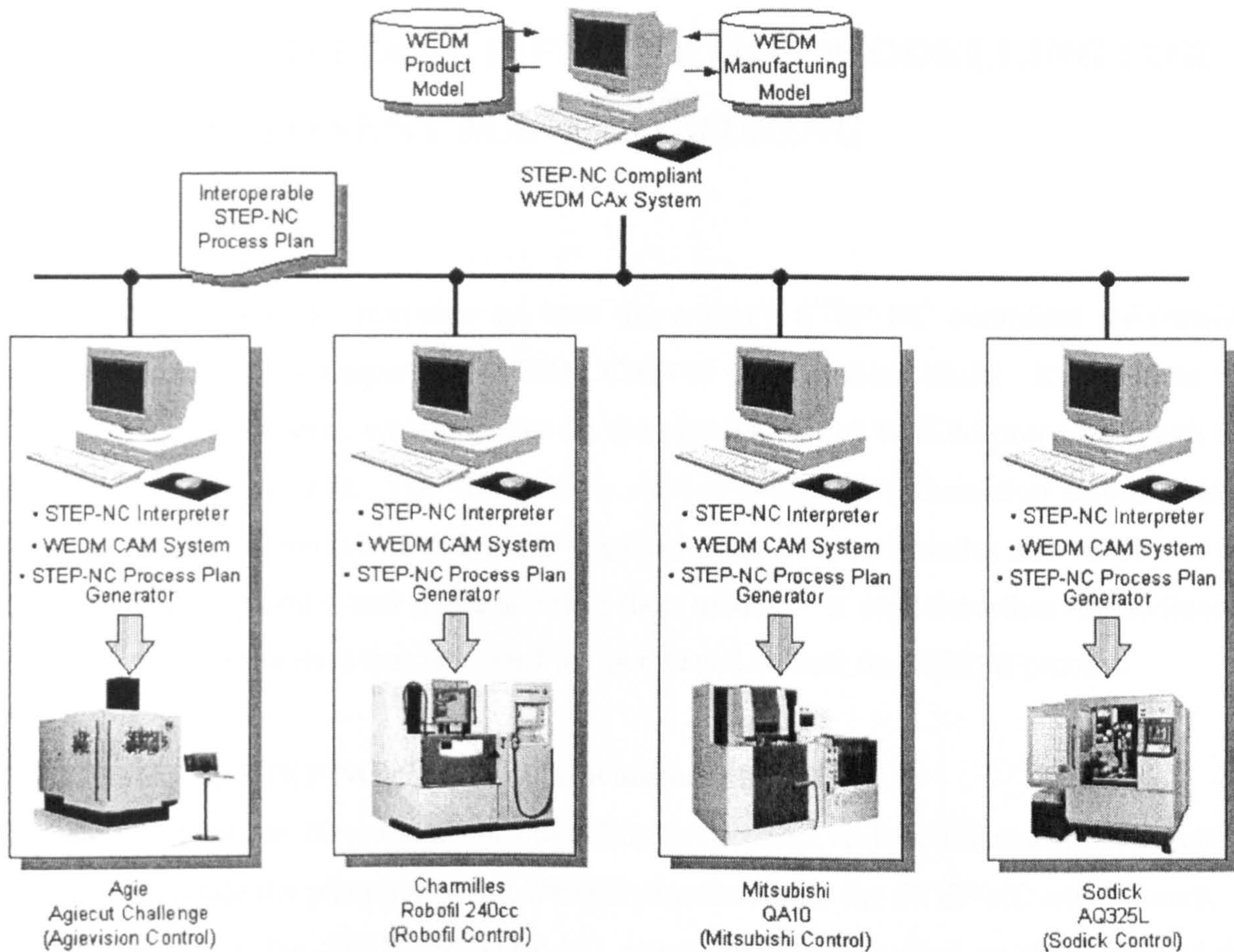


Figure 5.5 Interoperable manufacturing environment for WEDM process

The key factor of attaining data interoperability is to adopt a good infrastructure, a proper communication tool, and a standard product data representation that can be accepted by most CAD/CAM software systems (Chao and Wang 2001). The author expects that the user-driven STEP-NC data interface will enable the proposed system framework to meet the interoperability requirement through the use of the neutral file format of representing the information for WEDM CNC manufacturing. This is in contrast to the machine-driven ISO 6983 data interface, which allows the incorporation of vendor-specific format or code to fully describe the WEDM process. Hence, by complying with the STEP-NC approach of CNC manufacturing, different WEDM CAD/CAM software companies and CNC vendors will be able to exchange product and manufacturing information explicitly without making compromises on disclosing their proprietary manufacturing methods and procedures.



## Chapter 6

# STEP-NC COMPLIANT INFORMATION MODELLING FOR WEDM COMPONENT MANUFACTURING

### 6.1 Introduction

This chapter provides an overview on how the author's STEP-NC compliant information models can be used to support the WEDM CAD to CNC process chain. It introduces the research from a viewpoint, which focuses on the planning of the WEDM process through the use of information models. The viewpoint is used to define the information models, which are based on parts 10 and 13 of ISO 14649 standard. This chapter includes an overview of the author's WEDM product and manufacturing data models. It also describes the additional information to the standard that is needed to operate and control the WEDM process.

### 6.2 Context for STEP-NC compliant information modelling

This section describes the context for modelling the product and manufacturing information needed to facilitate the planning of the WEDM process within the STEP-NC environment. It also describes how the STEP and STEP-NC standards have an effect on the design of the author's WEDM information models.

#### 6.2.1 *Integrated product and manufacturing information modelling*

Information modelling has been used to represent the manufacturing capabilities of the WEDM process. It assists in identifying the common information requirements before developing the machining process planning software applications. Hence, it should be recognised that the resultant information models are application and processing independent and form the basis for the design of application independent databases and interfaces (Toh *et al.* 1998). The common information requirements needed to execute and control the WEDM process have been divided into the PModel defining the design specification together with method of manufacture, and MModel relating to the process capabilities, as mentioned in section 5.2.1. However, the two information models are closely integrated, as the product information is required to support the determination of the process, whereas the manufacturing information is required to facilitate the optimisation of the design specifications and method of manufacture.



This has been made possible by the information modelling techniques, which simplify the representation of the integrated data structure and relationships for a variety of product design and manufacturing process applications. The information modelling tools used in this research included the EXPRESS language and the UML (Quantrani 2000), which are described in detail in chapter 7.

### 6.2.2 *STEP compliant product information modelling*

The STEP standard has strongly influenced the research in the area of specifying the information of a WEDM product for CNC manufacturing. It seeks to provide a complete and unambiguous representation of the WEDM product geometrical information by using a feature-based component representation based on the object-oriented EXPRESS language. A feature-based element is considered as a geometric primitive, characterizing it as a component building block embodying the meaningful information for the exchange and interpretation of the design intent to other applications. In addition, STEP makes a clear distinction between the information model and the implementation method allowing the product data model (PDM) to be organised with a unique set of entities for the WEDM process. As a result, richer product information can be expected and exchanged consistently between the different stages of the WEDM product life cycle from product designing to product manufacturing.

In this thesis, the PModel holds the detailed information relating to the product, which is clearly distinguishable from the PDM, which provides a data structure and relationship that enables the essential characteristics of a product to be captured (Borja *et al.* 2001). The research work carried out by Ming *et al.* (1998) has provided a significant insight into the appropriate breakdown of the WEDM PModel. They developed an object-oriented STEP based PModel depicting the geometrical information and the semantic representation of the part embodying the nominal shape, form feature, dimension and tolerance, material, and surface information for a CAPP system. These elements have been used to represent the basic attributes of the author's PModel.

### 6.2.3 *STEP-NC compliant manufacturing information modelling*

In addition to STEP compliant product modelling, the STEP-NC standard has effected the common consensus of establishing the structure of the manufacturing information supporting the WEDM process. It has been developed to standardise the information content and data structure describing the various machining process planning activities for CNC

manufacturing. The data structure of STEP-NC, which describes the characteristics of the CNC machining process has been extended from the STEP PDM in order to improve the integration of the CAD to CNC process chain. It also helped in the studying of the impact of the functional design decisions on the manufacturing technologies and processes by setting the design criteria in the context of the manufacturing facilities.

Several researchers (Borja *et al.* 2001, Gao and Huang 1996, Giachetti 1999, Ming *et al.* 1998) have modelled the manufacturing process capabilities in the context of the process representing the functions and characteristics of the manufacturing activities, and the resource representing the constraints of the manufacturing facilities. Some researchers (Liu and Young 2004, Molina *et al.* 1995, Molina and Bell 1999) have identified an object-oriented MModel for capturing the data, information and knowledge related to the manufacturing resources, processes and strategies within an enterprise. These research areas have been utilised for the modelling of the manufacturing information about the machine, cutting tool, machining process and operation have contributed to the development of the author's MModel supporting the generation of the WEDM machining schema in an integrated design and process planning environment.

### 6.3 STEP-NC compliant information modelling for WEDM process

This section outlines the author's information models supporting WEDM component manufacturing based on STEP and STEP-NC standards.

#### 6.3.1 WEDM information modelling

The information models described in this research apply the relevant STEP-NC standards to support decision-making relating to the WEDM process planning. As mentioned in section 4.5.3, STEP-NC has a common source of well-defined and structured information capable of satisfying the information requirements needed to carry out a number of CNC machining processes. Part 13 of the ISO 14649 standard has been dedicated to the WEDM process and is still in the development phase. The Swiss partners of the IMS project (Richard *et al.* 2004) are the developers of the standard. Although the standard is still under development, the overall structure and content is expected to remain mainly unchanged.

The author's proposed WEDM information models are shown in figure 6.1 and consist of the PModel and MModel based on the STEP-NC standards. The manufacturing view attribute



residing in the PModel embodies the relevant instances of the MModel. It captures the generic manufacturing information in the PModel to promote interoperable manufacturing of a WEDM part. This is consistent with other researchers (Borja *et al.* 2001, Lim *et al.* 1997) who have argued that the information held in the MModel must be made available to the product designers during product development phase in order to facilitate design for manufacture.

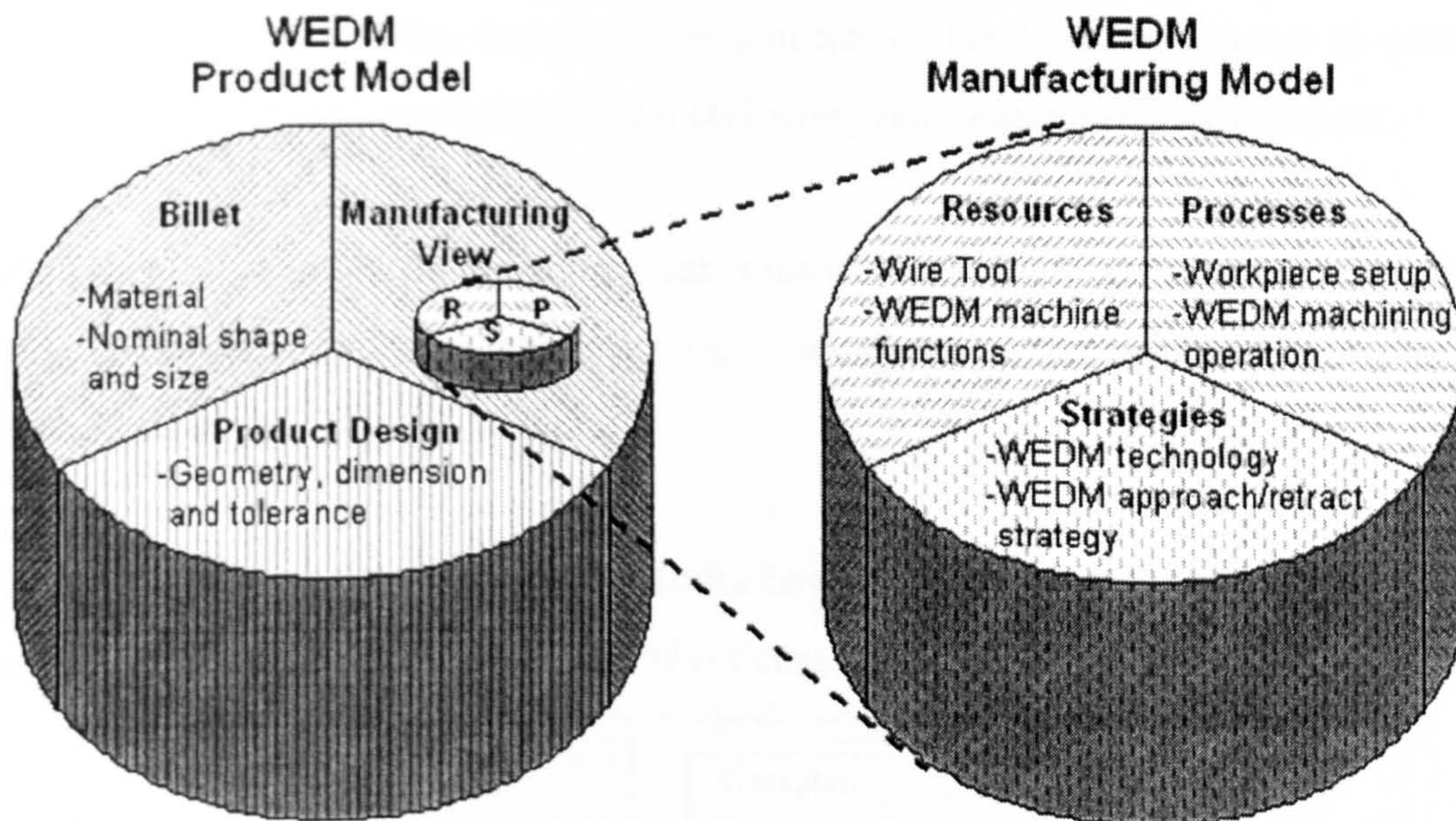


Figure 6.1 STEP-NC compliant WEDM information models

### 6.3.2 WEDM manufacturing model (MModel)

The WEDM MModel captures the common information describing the manufacturing capabilities of the WEDM process. It has been adapted from Molina *et al.* (1995), whose MModel described the manufacturing capability of a particular facility in terms of its manufacturing resources, processes and strategies. As such, the WEDM MModel also considers the physical (resource) and functional (process) properties of the machining process. It also takes into account the representation of the feasible WEDM machining schemas (strategies) based on the composition of the resources and processes. This is due to the different combination of WEDM resources and processes having a direct effect on the WEDM machining schemas of achieving the machining targets, such as the number of cuts required to obtain a desired surface finish. The data structure of the WEDM MModel that defines the characteristics of the process is illustrated in figure 6.2. The knowledge about the WEDM process is organised in an object-oriented manner enabling the process planner to select the appropriate strategies based on the array of available resources and the feasible



processes to machine a part. The WEDM MModel has been made up of the following attributes:

*WEDM resources* – model the physical constraints imposed on the WEDM process to machine the required part, e.g. *wire\_tool* and *wire\_edm\_machine\_functions*.

*WEDM processes* – model the functional capabilities of the WEDM process to perform the machining operations, e.g. *workpiece\_setup* and *wire\_edm\_machining\_operations*.

*WEDM strategies* – model the machining schemas of the WEDM process based on the given WEDM resources and processes, e.g. *wire\_edm\_approach/retract\_strategy* and *wire\_edm\_technology*.

These three attributes of the WEDM MModel have covered all the essential manufacturing information needed to carry out the WEDM process.

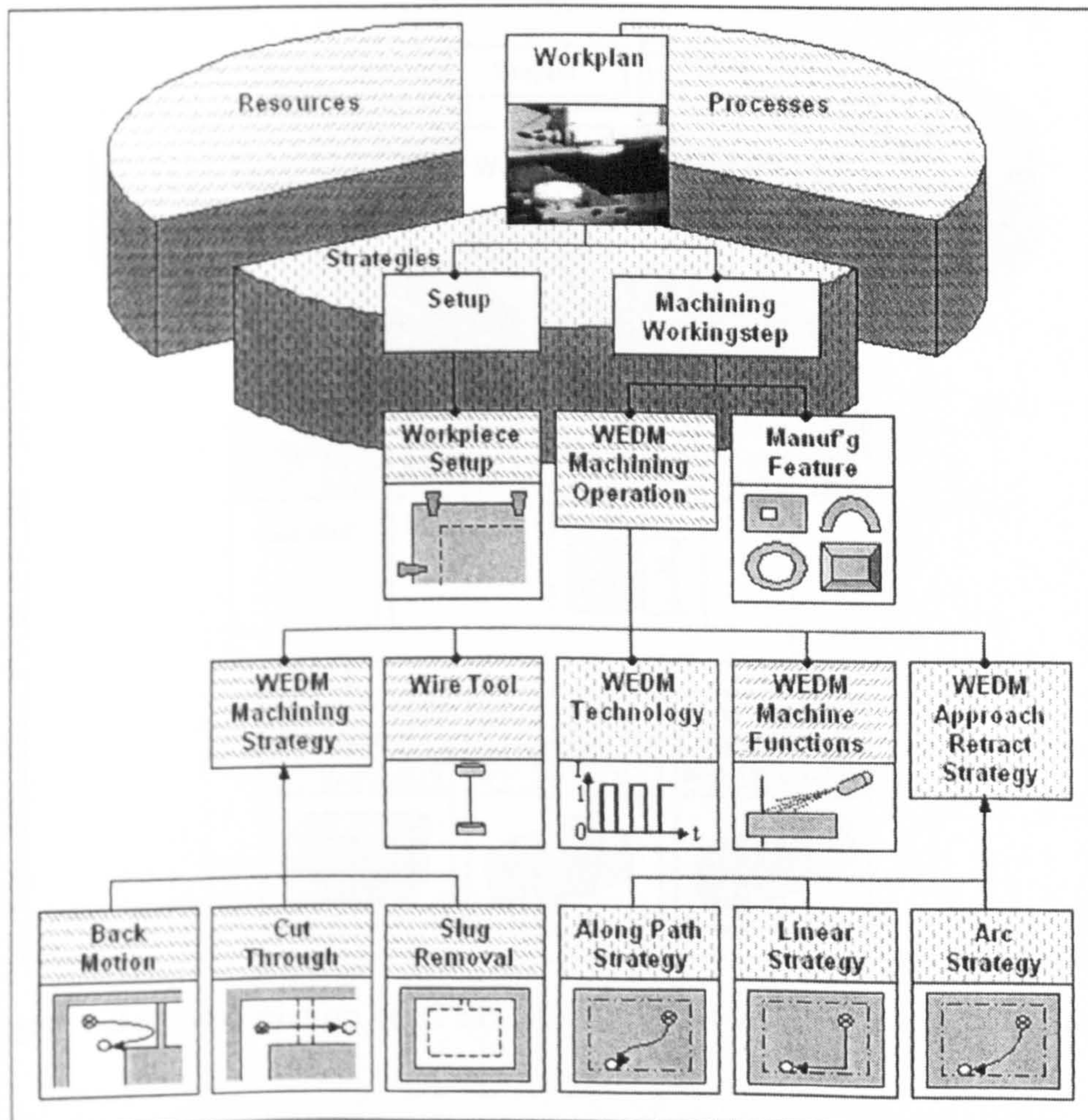


Figure 6.2 Representation of STEP-NC compliant WEDM manufacturing data model



### 6.3.3 WEDM product model (PModel)

The WEDM PModel facilitates the management of the product information and knowledge for the various product life cycle activities. It models all the essential properties and characteristics of a WEDM part. These include the representation of the billet, in terms of the material, nominal shape and size, together with the product design in relation to the geometries, dimensions and tolerances (G, D & T) of the part to be machined. In addition, a manufacturing view of the part is offered to the PModel in order to serve as a means of integrating the PModel and the MModel. Since the PModel has been ultimately used to satisfy the information requirements of the manufacturing process at the later stage of the process chain, it is vital to set it in the context of the selected process to manufacture the part. By doing so, the manufacturing view supports the preliminary and interoperable process planning in the early product development stage in an integrated manufacturing environment. This approach is consistent with the work done by Liu and Young (2004), who have also provided a manufacturing view in their PModel to support global manufacturing co-ordination decision-making.

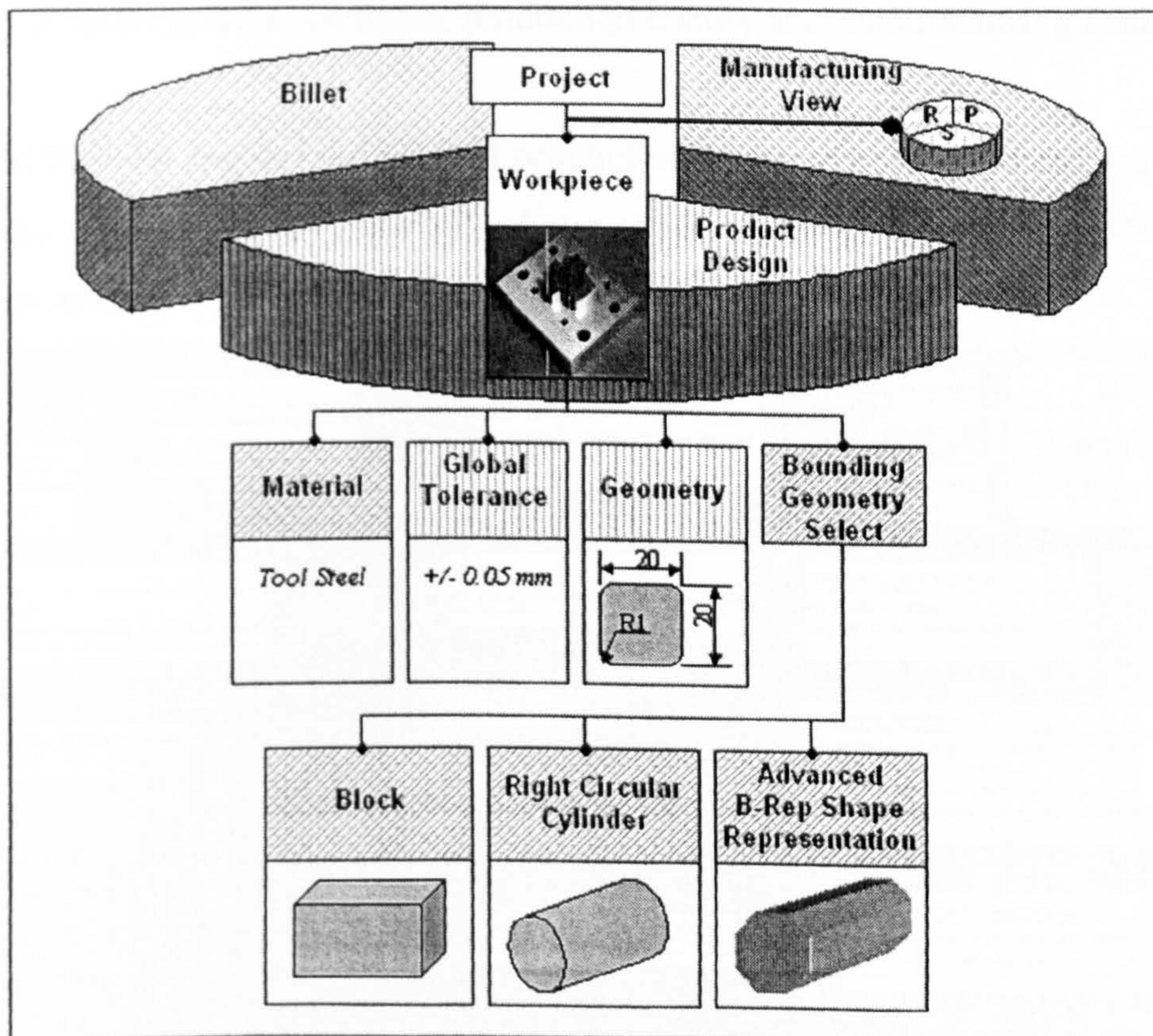


Figure 6.3 Representation of STEP-NC compliant WEDM product data model



Figure 6.3 shows the data model of the WEDM PModel offering a manufacturing view of a part. The MModel residing in the PModel shares the same data structure as the main MModel, which holds the actual manufacturing information in the application domain and works in harmony with the PModel. The WEDM PModel is made up of the following attributes:

*WEDM billet* – models the characteristics of raw material, which have an effect on the selection of cutting parameters (technology), e.g. material and nominal shape and size.

*WEDM product design* – models the G, D & T of the WEDM part, which have a direct influence on the determination of the machining operations and the selection of the cutting parameters, e.g. the surface finishing quality and the dimensional accuracy.

*WEDM manufacturing view* – models the relevant instances of the MModel, which allow an early assessment of the manufacturability of the part and the interoperability of the machining workplan, e.g. interoperable workplan, production history and manufacturing features.

The WEDM PModel enables the WEDM product information to be captured and represented through these three attributes. Figure 6.4 shows the overview of the two STEP-NC compliant WEDM data models.

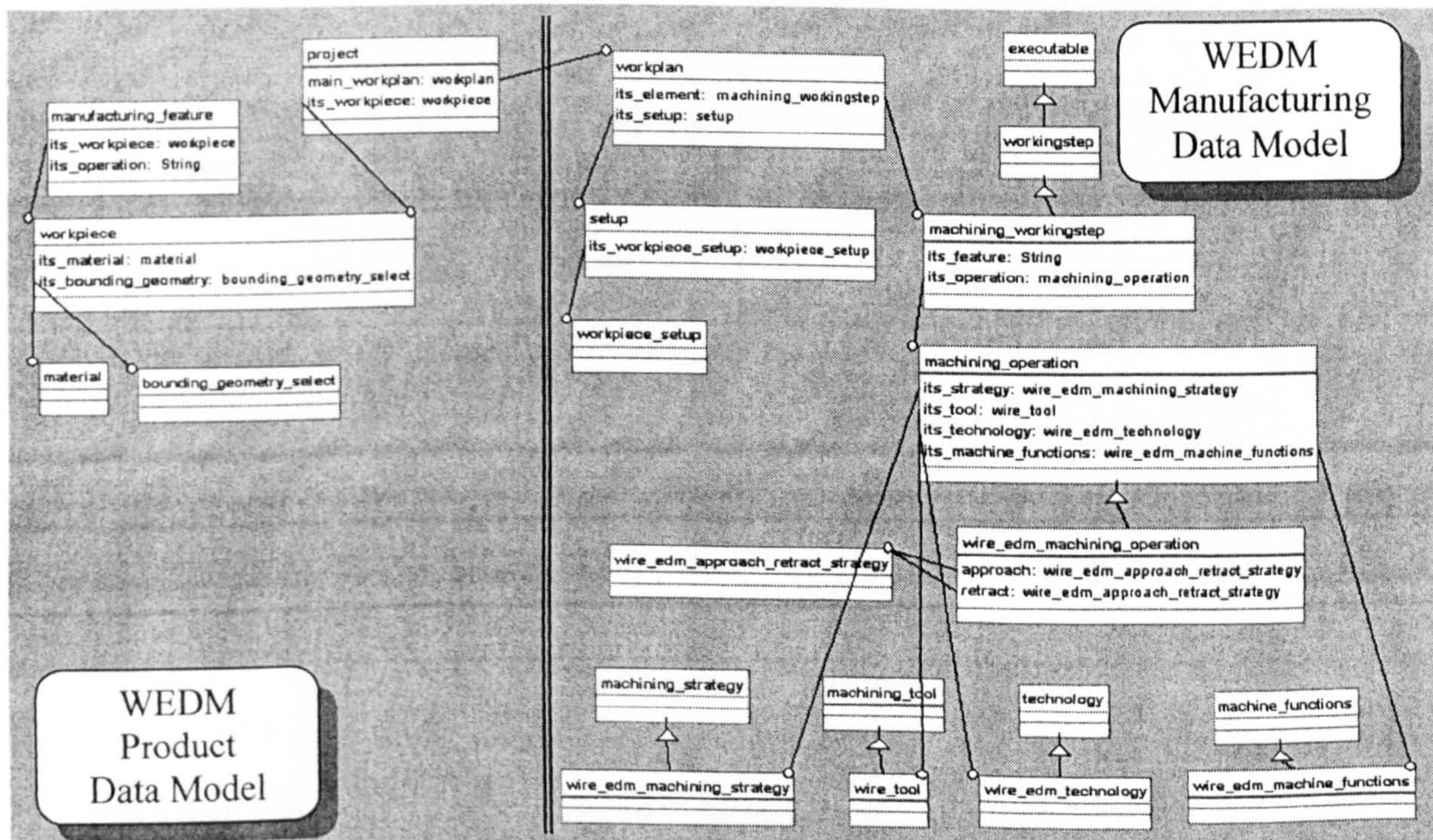


Figure 6.4 Overview of STEP-NC compliant WEDM information data models



The STEP-NC standard has provided the WEDM information models with a bounded set of data structures for CNC manufacturing. As shown in figure 6.4, the PDM is headed by the *Project* class, which is the top-level entity of the STEP-NC process plan, whereas the MDM is led by the *Executable* class, which is the base entity of all executable objects initiating actions on the machine (ISO14649-10 2004).

#### 6.4 WEDM extended information models

In the author's opinion, the current data model specified in the ISO/DIS 14649-13 needs to be extended in order to fully support the WEDM machining operations. This is due to the lack of common product and manufacturing information that allows the CNC machine to intelligently operate the WEDM process. Figure 6.5 shows the additional information represented in their respective information models and is illustrated by the dotted lines and textboxes. This information has been identified by the author's use of the commercial WEDM CAD/CAM systems, namely the PEPS Solid Cut Wire EDM (Production Engineering Productivity System) (Camtek 2005) and PC FAPT Cut i (Fanuc Automatically Programmed Tools) (600Centre 2005).

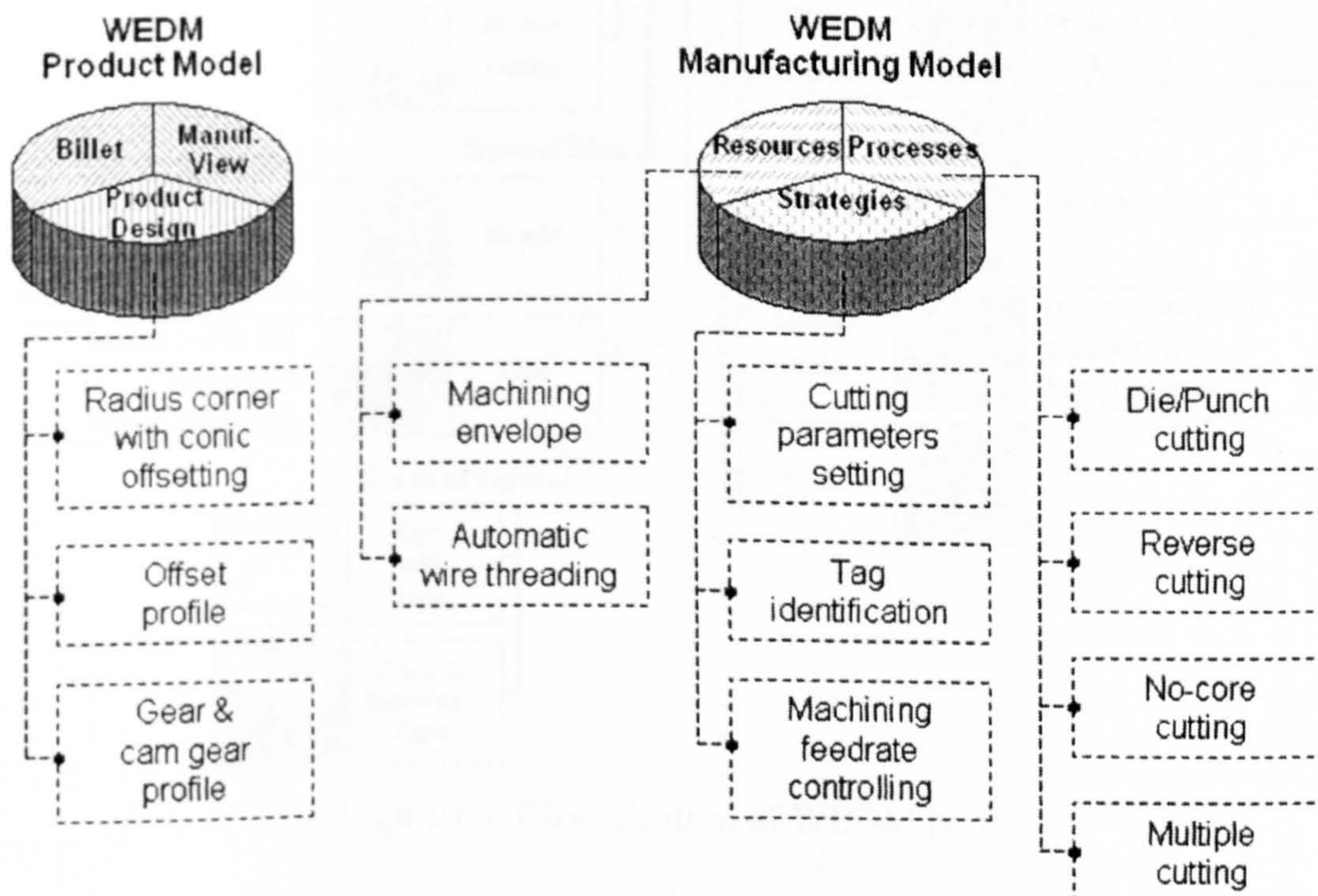


Figure 6.5 WEDM extended information models

As identified above, the extended information models are based on the machining/programming parameters of PEPS Solid Cut Wire EDM (PEPS Solid Cut) and the



PC FAPT Cut i (FAPT) CAD/CAM systems. The inclusion of this additional information makes it possible to facilitate the integration of the PModel and the MModel with these commercial CAD/CAM systems. The detail of these systems will be discussed in depth in chapter 8, which describes the testing of the prototype system.

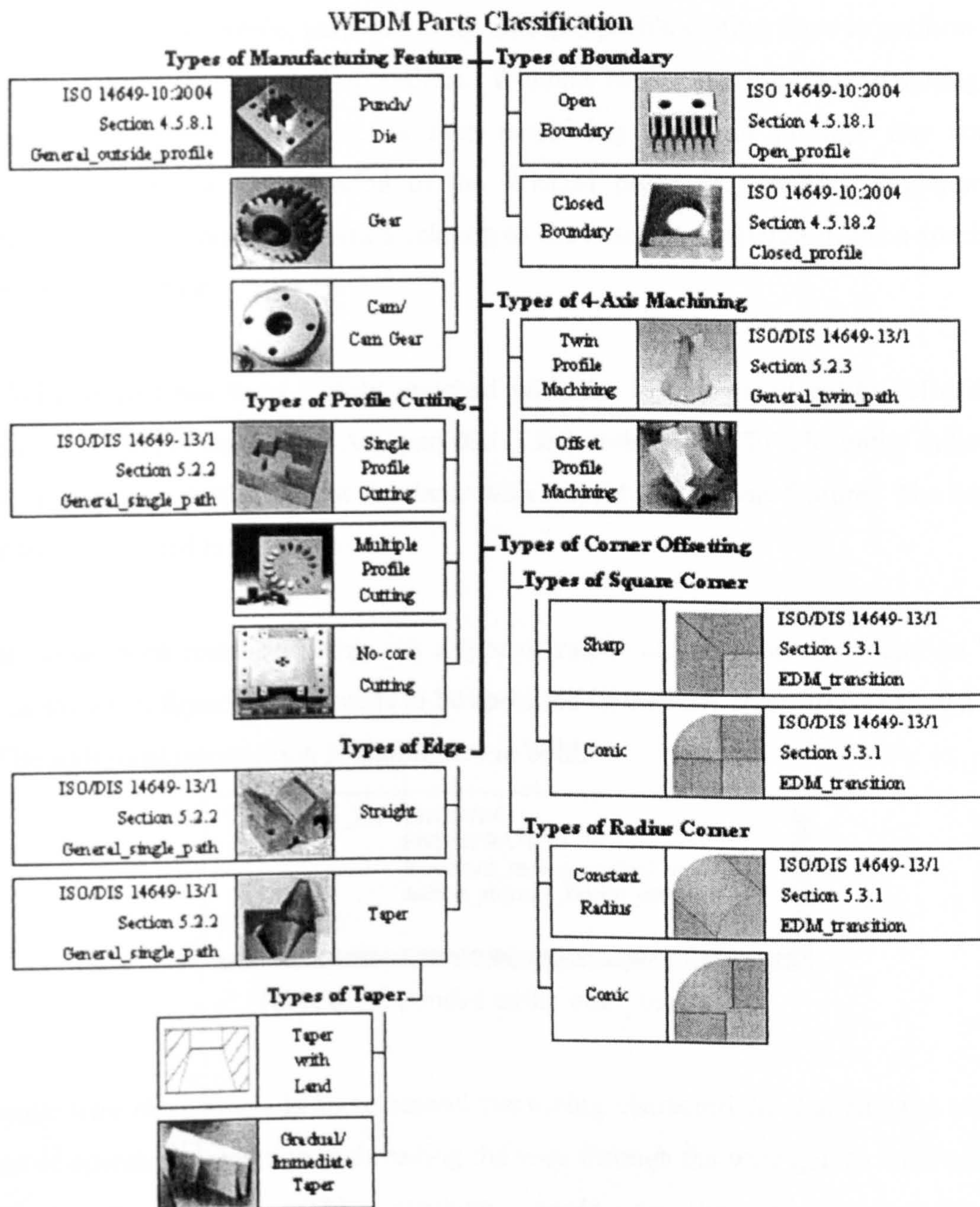


Figure 6.6 Classification of WEDM parts

In addition, a classification of the various industrial parts manufactured by the WEDM process has been identified by the author and has been mapped onto the STEP-NC standard in order to determine the additional information that has yet to be specified in ISO/DIS 14649-13. Figure 6.6 shows the author's classification of the WEDM parts under the various



headings including the types of manufacturing feature, boundary, profile cutting, 4-axis machining, edge and corner offsetting. The classification is also based on the approach, in which PEPS Solid Cut and FAPT program the machining operations for these parts. Such an approach simplifies the programming of the machining operations that are specific to the classified parts. For example, parts requiring multiple profile cutting have to perform the tag cutting and manual slug removal operations. Whereas parts requiring no-core cutting do not have to perform these operations, as such machining does not produce any core/slug. Therefore, through the classification of the WEDM parts, the specific programming of together with the relevant information relating to the machining operation for a specific part can be easily identified.

Each WEDM part has been closely matched with the feature-based entity defined in the respective ISO 14649 standards. Any part that is left without a STEP-NC entity indicates the missing information in the current standards with respect to that part feature. The additional information identified is as follows:

*Radius corner with conic offsetting* – is a type of radius corner generally found on WEDM parts, as shown in figure 6.6. It needs to be specified in the *edm\_transition* as shown in table 6.1. The additional information is highlighted in bold.

TYPE EDM_TRANSITION =
ENUMERATION OF
(constant_radius, conical, sharp,
<b>radius_corner_conic_offsetting</b> );
END_TYPE;

Table 6.1 Extended entity edm\_transition

*Automatic wire threading* – is an automatic machining characteristic that helps to reduce the amount of operator’s invention in threading the wire through the wire guides with/without the workpiece in place. This attribute needs to be added in the entity *wire\_edm\_machining\_functions* as shown in table 6.2.

*Machining envelope* – refers to the size of the machining area, which is determined by the WEDM machine axes including the x, y, z, u and v axes. It needs to be specified as one of the attributes in the *wire\_edm\_machining\_functions* as shown in table 6.2.



ENTITY wire_edm_machine_functions	
SUBTYPE OF (machine_functions);	
coolant:	BOOLEAN;
coolant_pressure:	OPTIONAL pressure_measure;
lower_nozzle:	BOOLEAN;
upper_nozzle:	BOOLEAN;
nozzle_gap:	OPTIONAL length_measure;
auto_wire_threading:	BOOLEAN;
max_x_axis:	length_measure;
max_y_axis:	length_measure;
max_z_axis:	length_measure;
max_u_axis:	length_measure;
max_v_axis:	length_measure;
max_taper;	plane_angle_measure;
other_functions:	SET [0:?] OF property_parameter;
END_ENTITY;	

Table 6.2 Extended entity *wire\_edm\_machine\_functions*

*Machine feedrate controlling* – is used together with an expert system to monitor and control the feedrate when machining parts with small corner, small radius, variable taper or variable thickness. It needs to be included in the *wire\_edm\_technology*, as shown in table 6.3.

*Cutting parameters setting* – refers to the setting of various machining parameters in order to achieve optimal cutting conditions and offsets, such as the pulse on/off time and working current, as shown in table 6.3. The parameter setting is primarily determined by the WEDM expert system, which differs from vendor to vendor.

ENTITY wire_edm_technology	
SUBTYPE OF (technology);	
small_corner_strategy:	OPTIONAL BOOLEAN;
small_radius_strategy:	BOOLEAN;
variable_taper_strategy:	BOOLEAN;
variable_thickness_strategy:	BOOLEAN;
pulse_on_time:	time_measure;
pulse_off_time:	time_measure;
working_current:	electric_current_measure;
other_generator_parameters:	OPTIONAL set [0:?] OF property_parameter;
END_ENTITY;	

Table 6.3 Extended entity *wire\_edm\_technology*

*Offset profile* – is a literally twisted WEDM part in which the top profile axially offsets from the bottom profile, as shown in figure 6.6. The basic attributes for the offset profile are shown in figure 6.7.



*No-core cutting* – refers to the machining of a pocket through gradual enlargement without producing any core/slug, as shown in figure 6.6. It needs to be added as one of the *machining\_features*, as shown in figure 6.7.

*Gear, cam and cam gear profiles* – are some of the most commonly machined parts carried out by the WEDM process, as depicted in figure 6.6. This is largely due to the intricate teeth, which are very difficult to be machined by traditional material removal processes. The cutting of the gear profile needs to be added to the *machining\_feature*, as shown in figure 6.7. It has been prefixed with an ‘EXT’ (extended) in order to distinguish from the STEP-NC entities.

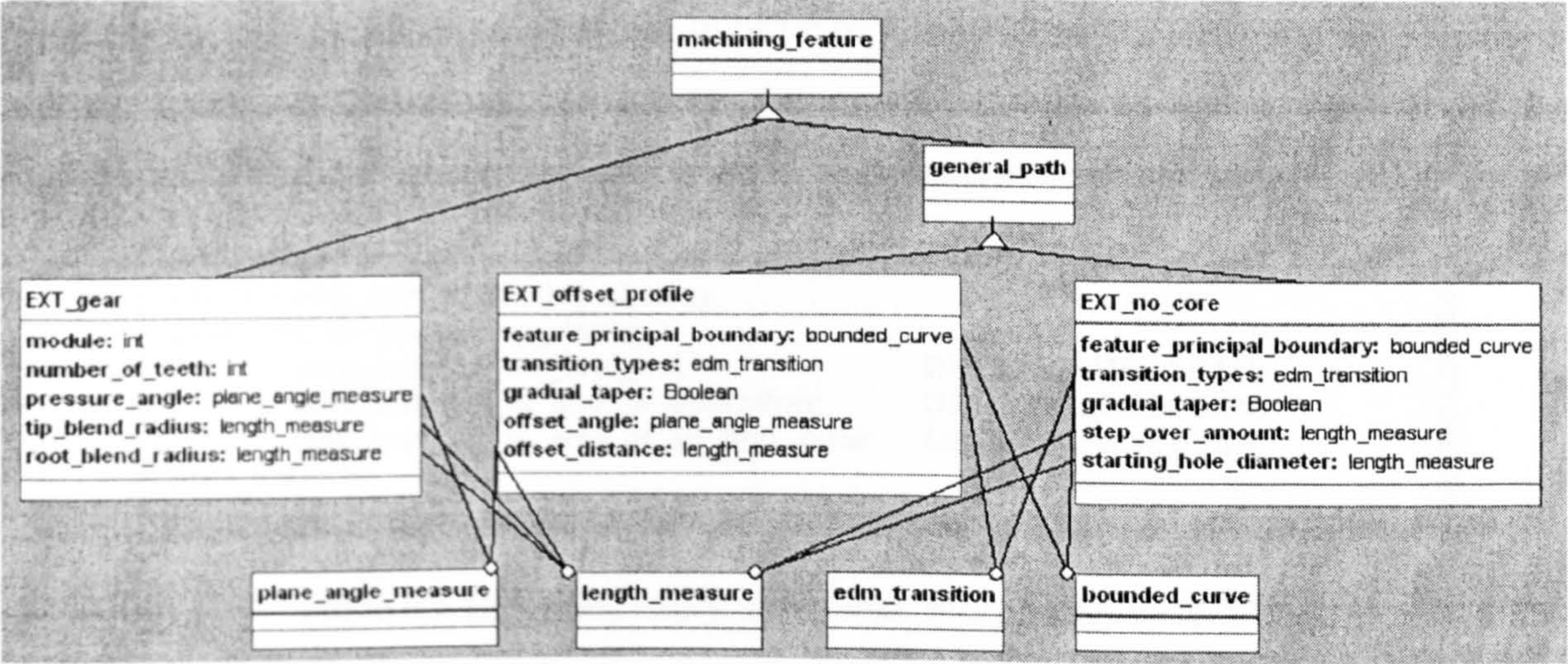


Figure 6.7 Gear, offset\_profile and no\_core machining features

*Die/Punch cutting* – has a different effect on the compensation of the offsets caused by the sparking zone when machining a punch or a die. Depending on the cutting direction, the side (left/right) in which the compensation is to be made needs to be defined in the *wire\_edm\_machining\_operation*, as shown in table 6.4.

*Tag identification* – is a machining characteristic, which identifies the tag position and the need to have multiple tags when machining a large component. It needs to be included in the *wire\_edm\_machining\_operation*, as shown in table 6.4.

*Reverse cutting* – reduces machining time by performing machining with a different set of cutting conditions and offsets on the returning toolpath. This needs to be added into the *wire\_edm\_machining\_operation*, as shown in table 6.4.



ENTITY wire_edm_machining_operation	
SUBTYPE OF (machining_operation);	
offset_length:	OPTIONAL length_measure;
offset_side:	String;
approach:	OPTIONAL wire_edm_approach_retract_strategy;
retract:	OPTIONAL wire_edm_approach_retract_strategy;
thread_point:	LIST OF [1:2] OF cartesian_point;
cut_end_point:	SET OF [0:?] OF cartesian_point;
tag_escape_amount:	length_measure;
reverse_cutting:	BOOLEAN;
END_ENTITY;	

Table 6.4 Extended entity *wire\_edm\_machining\_operation*

*Multiple cutting* – performs an order of cutting on multiple punches/dies on the same workpiece in a single setup, as shown in figure 6.6. The strategies optimising the amount of machine operator’s invention on the manual removal of the slug/waste material and the manual control of the machine thereafter need to be defined as shown in table 6.5.

ENTITY wire_edm_machining_strategy	
SUBTYPE OF (machining_strategy);	
wire_cut_tag_on_first_cut:	OPTIONAL BOOLEAN;
wire_cut_tag_at_end_of_operation:	OPTIONAL BOOLEAN;
wire_cut_tag_at_end_of_all_first_cuts:	OPTIONAL BOOLEAN;
END_ENTITY;	

Table 6.5 Extended entity *wire\_edm\_machining\_strategy*

The additional information that is crucial to the WEDM operation has been identified to allow the CNC to intelligently operate the process. It adds on to the existing information specified in the drafted ISO 14649-13, which is still currently under development. This information has been represented in an object-oriented manner. The definition of the common technological parameters for specifying the WEDM generator setting is represented in the *wire\_edm\_technology* whereas the standardisation of the proprietary strategies for machining specific features, such as sharp corner is presented in the *wire\_edm\_machining\_strategies*. This complies with the STEP-NC approach of reducing all the essential WEDM process data to its common denominator facilitating the reuse and reconfiguration of the data according to the different functions of the CAD to CNC software applications. This additional information is considered as a valuable contribution from this research work to the development of the ISO/DIS 14649-13 standard.



## Chapter 7

# COMPUTATIONAL ENVIRONMENT FOR STEP-NC COMPLIANT WEDM CAX PROTOTYPE SYSTEM

### 7.1 Introduction

This chapter describes the computational environment for the STEP-NC compliant WEDM CAX prototype system based on the framework and the information models identified in chapters 5 and 6 respectively. The prototype system is referred to as Wire SNIPs (STEP-NC interoperable process planning prototype system for the wire-cutting EDM process) throughout the thesis. Wire SNIPs has been constructed through the use of the Java programming language and the ObjectStore database management system (DBMS) to capture and manage the essential information and knowledge supporting the various WEDM process planning activities. The chapter describes the development, functional and operational structure of Wire SNIPs to generate a STEP-NC process plan for WEDM component manufacturing.

### 7.2 Overview of Wire SNIPs

This section provides an overview of Wire SNIPs by briefly describing the various tools used to develop the prototype system. It also describes the representation of the WEDM information models needed to drive Wire SNIPs through the use of UML.

#### 7.2.1 *Basic components of Wire SNIPs*

Wire SNIPs has been developed to demonstrate the viability of the product and process knowledge residing in the author's WEDM information models based on STEP-NC standards. The design has been based on the framework outlined in chapter 5 and the WEDM PModel and MModel outlined in chapter 6. Figure 7.1 depicts the methodology of designing the Wire SNIPs based on the system framework and the WEDM information models. The system framework provides the operational structure, which supports the decision-making and the generation of STEP-NC process plan relating to WEDM process planning, see figure 5.2. These process planning activities, their relationships and information flows have been illustrated by the IDEF0 diagram as an abstract in figure 5.3 to the detail in figure 5.4. Such an approach of differentiating the various process planning activities facilitates the

development of the Wire SNIPS, in terms of database management. As for the instances of WEDM PModel and MModel, they have been represented by the UML class diagram, see figure 6.4, and will be further discussed in the following section 7.2.2.

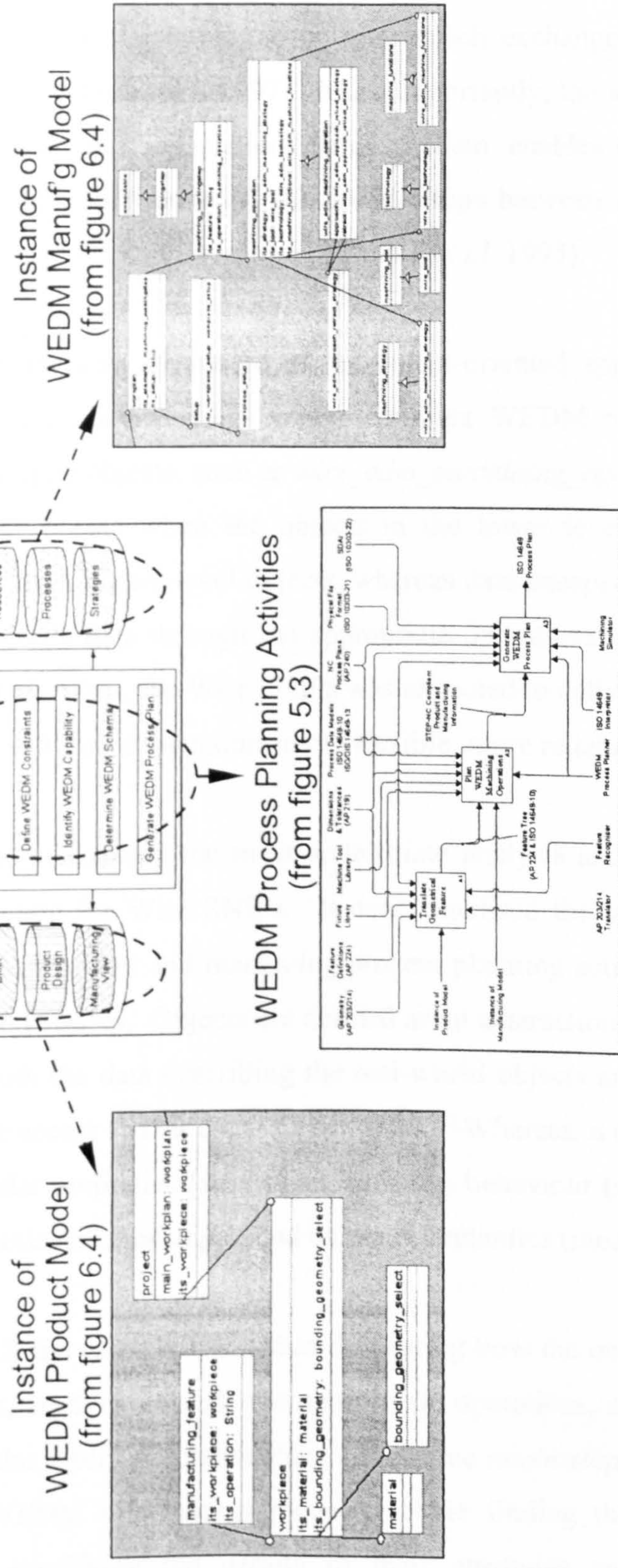
The realisation of the system together with the supporting information models has been systemically designed through the use of the UML class diagrams, the ObjectStore DBMS (Progress 2005) together with the Java programming language (Sun 2005). UML is an industry-standard and object-oriented modelling language that provides a reliable architecture for the specification, visualisation and documentation of information models. It has enabled the design along with the structure of the product and process knowledge to be explicitly illustrated and easily implemented in the DBMS. The ObjectStore DBMS is employed in the system to store, modify and extract data from the database, thus allowing it to be shared among multiple applications. As for Java, it is the nerve of the system performing the main planning task of matching the applicable manufacturing process capabilities to product design specification. The underlying principle of planning a WEDM process is made by invoking the rules of sequencing a logical machining route and imposing the technological machining criteria, such as the required surface finish and minimum number of cuts.

The main objective of Wire SNIPs is to prove that the author's WEDM PModel and MModel based on the STEP-NC standards can be used to generate a STEP-NC process plan for WEDM component manufacturing. This has been achieved through an interactive software system, which makes the various process planning decisions and maps out a feasible process plan. Wire SNIPs was capable of determining the detailed WEDM operations based on the essential product and process information captured from the system users. Such capability has been made possible by making the following assumptions:

- i. Machining method was limited to die-opening cutting
- ii. Machining processes were limited to 3-axis WEDM machining
- iii. Machining processes were completed in single setup
- iv. Cutting modes were standardised to roughing, finishing and surface finishing
- v. Cutting conditions were generated automatically
- vi. Product information was extracted from feature-based component data
- vii. Feature-based component data was transformed from a CAD database
- viii. Translation of feature-based component has been carried out
- ix. Manufacturing resource allocation was not affected by resource availability



System Framework  
(from figure 5.2)



## Wire SNIPs

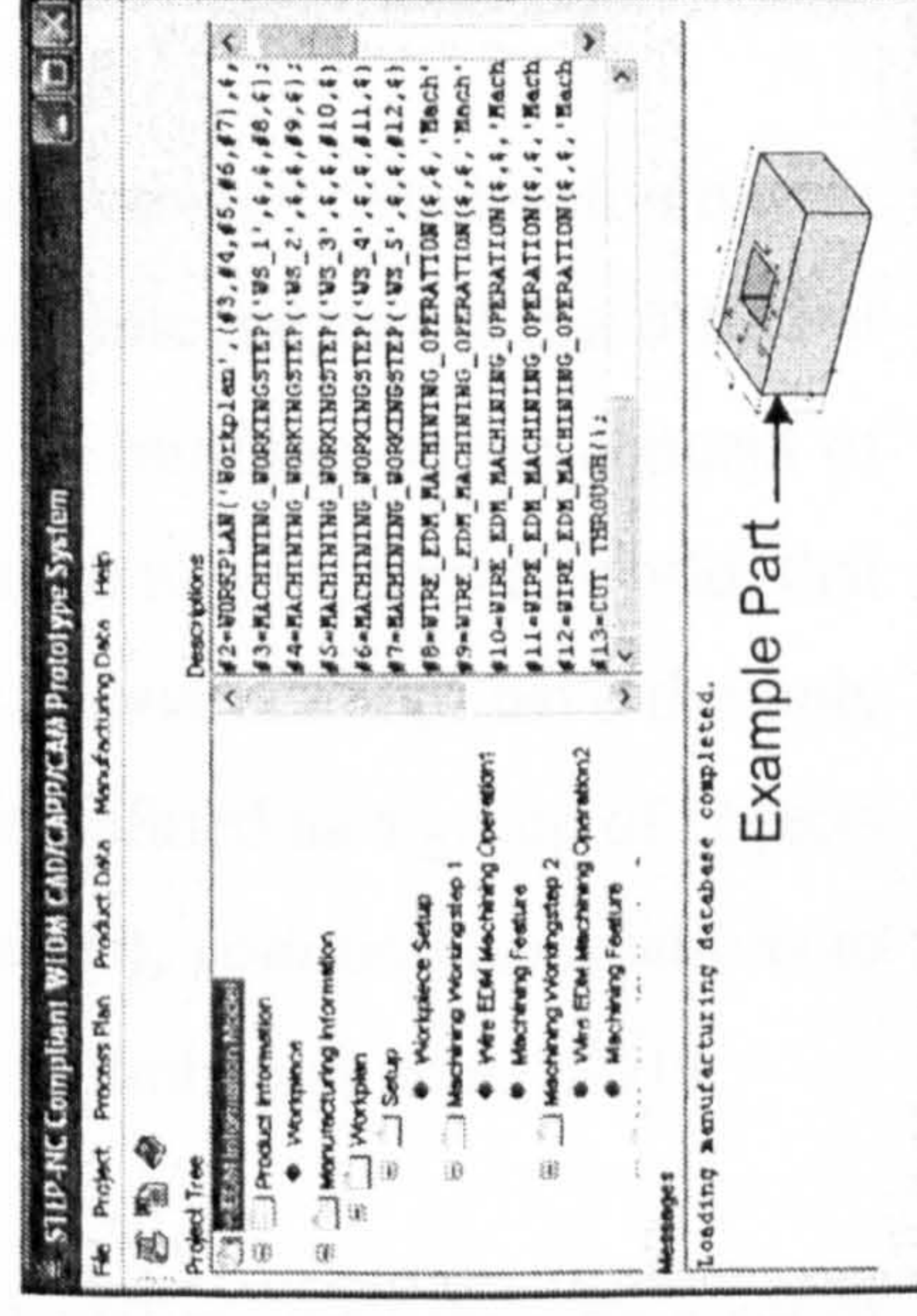


Figure 7.1 The design of Wire SNIPs based on the system framework and the WEDM information models



### 7.2.2 Representing WEDM information models in UML

The object-oriented approach has provided the fundamental building blocks of the WEDM information models for the development of the Wire SNIPs. It views the process planning system as a set of interrelated objects, which exchange messages during process planning (Sormaz and Khoshnevis 1997). More importantly, the ability to create a number of objects, and make complex associations between them, enables users to more realistically represent the capabilities of resources, the relationships between resources and to map from process requirements to suitable resources (Molina *et al.* 1995).

However, the key advantage of the object-oriented approach is that data inheritance and encapsulation characteristics enable complex WEDM objects to be defined by combining several simpler objects, such as *wire\_edm\_machining\_operation* as shown in figure 7.2. Data inheritance occurs when the objects in the lower level of the hierarchy inherit common attributes from higher-level objects, whereas data encapsulation only allows the manipulation of the object's data through the appropriate operations; external manipulation of the data is not allowed. Thus, the Wire SNIPs was expected to deliver such benefits, making the process planning software applications more flexible, more reliable and faster to develop.

UML was considered the most appropriate analysis and design method for developing the data structure for Wire SNIPs. It conceptualised the seamless integration of the different WEDM part design and machining process planning activities by building on the concept of objects and classes. Objects are defined as an abstraction of some thing in the real world, that carries both the data describing the real-world objects and the operations that have the only allowable access to that data (Brown 2002). Whereas, a class is defined as a group of objects with similar properties (attributes), common behaviour (operations), common associations to other objects (relationships), and common semantics (meaning) (Rumbaugh *et al.* 1991).

Figure 7.2 shows a class diagram illustrating how the object identifies itself through a set of attributes, behaves through the appropriate operations, and associates itself to other objects through the specified relationships. The three major steps used to generate the class diagram of the WEDM information models include finding the classes involved in the problem domain, specifying the details of their attributes and operations, and identifying the relationship among the classes as well as their roles and cardinalities (Zhao *et al.* 1999).



These steps have facilitated the WEDM information models to be constructed as objects coordinating in a manner satisfying a specific design or process planning application.

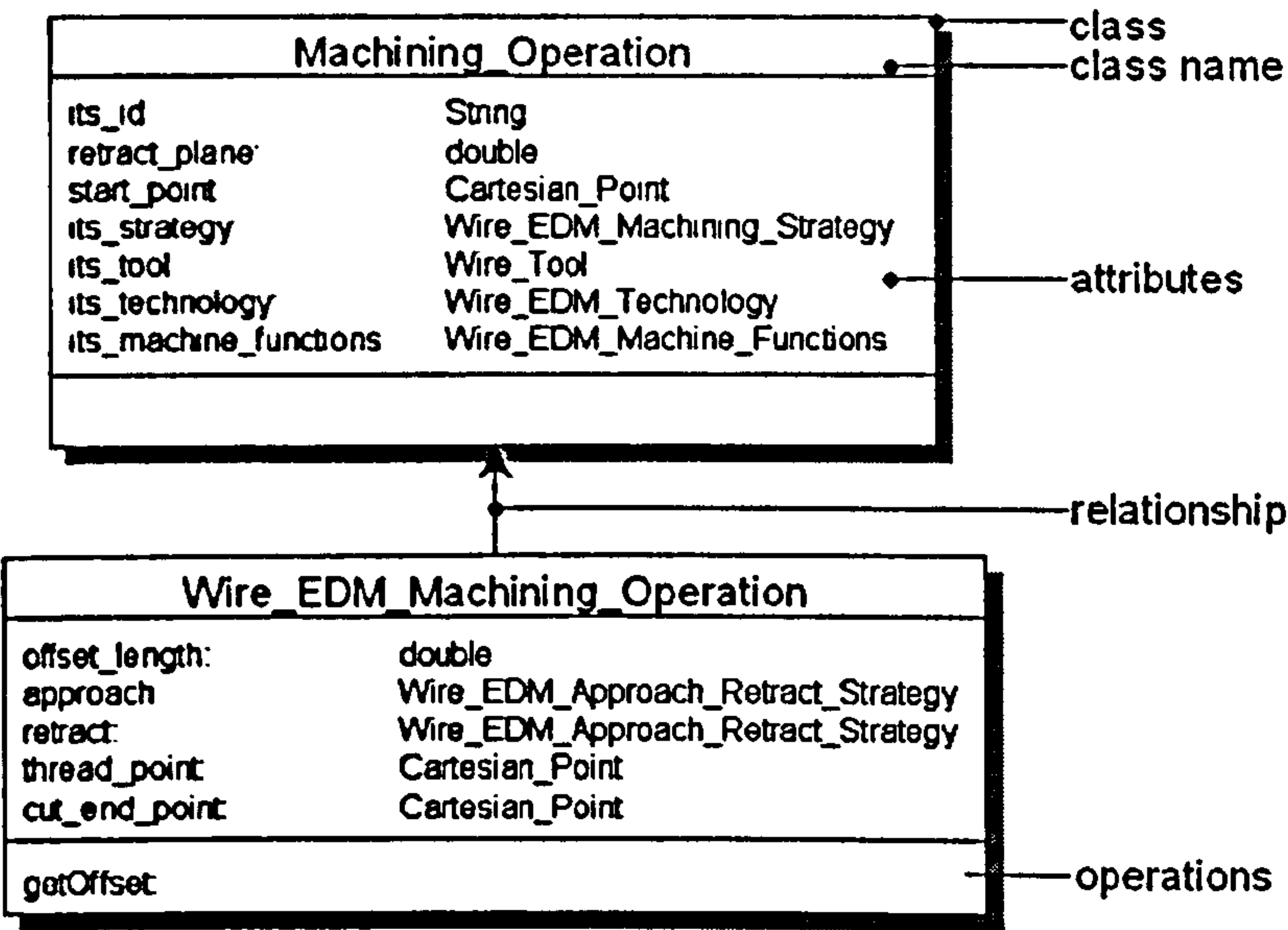


Figure 7.2 *Wire\_EDM\_Machining\_Operation* inheriting the *Machining\_Operation* attributes

UML has been used to represent the various objects in the WEDM manufacturing environment and the relationships between these objects. Each of the entities or data types specified in the WEDM PModel and MModel based on part 10 and part 13 of the ISO 14649 standard were mapped to the UML format and transformed into classes with logical links. Figure 7.3 shows the class diagram depicting the various classes of the interrelated WEDM product and process data types by using the ObjectStore Database Designer software (Progress 2005). As seen from the figure, the many links or associations between the low-level data types could be interpreted as the avoidance of data redundancy and the interdependence of the product and process knowledge supporting the WEDM process.

In addition, the UML representation of the WEDM information models serves as a logical data model, which can be used as the building blocks in the creation of an object-oriented DBMS (OODBMS). In the case of Wire SNIPs, it has helped to develop the logical database schema of the WEDM information models, which were directly implemented in the ObjectStore DBMS.







### 7.2.3 Developing Wire SNIPs database system

The OODBMS has allowed the easy storage and retrieval of WEDM information and knowledge captured from the system users in a structured manner. It retains all the key advantages of the object-oriented technology providing an efficient platform for information storage and retrieval based on data encapsulation and modularity. Gu *et al.* (1994) claimed that the administrative advantages were brought about by encouraging data modularity and by associating particular related knowledge with a specific set of data. As such, it gave OODBMS the performance advantage over its counterpart, the Relational DBMS, which required the mapping of objects to tables. As a result, the Relational DBMS slowed down the processing performance and increased the amount of code to be written due to the mapping of objects into rows and columns (ObjectStore 2003). Figure 7.4 illustrates how the OODBMS expedites the query of the Wire SNIPs database by traversing the 'tree-like' data structure or navigating from one node in the figure to another. As shown in the figure, the caching was the retention of data, usually in the application, to minimize network traffic flow and/or disk access. In addition, the OODBMS offered an ideal data storage solution for object-oriented programming languages such as Java and C++, which will be further discussed in depth in the subsequent section of this chapter.

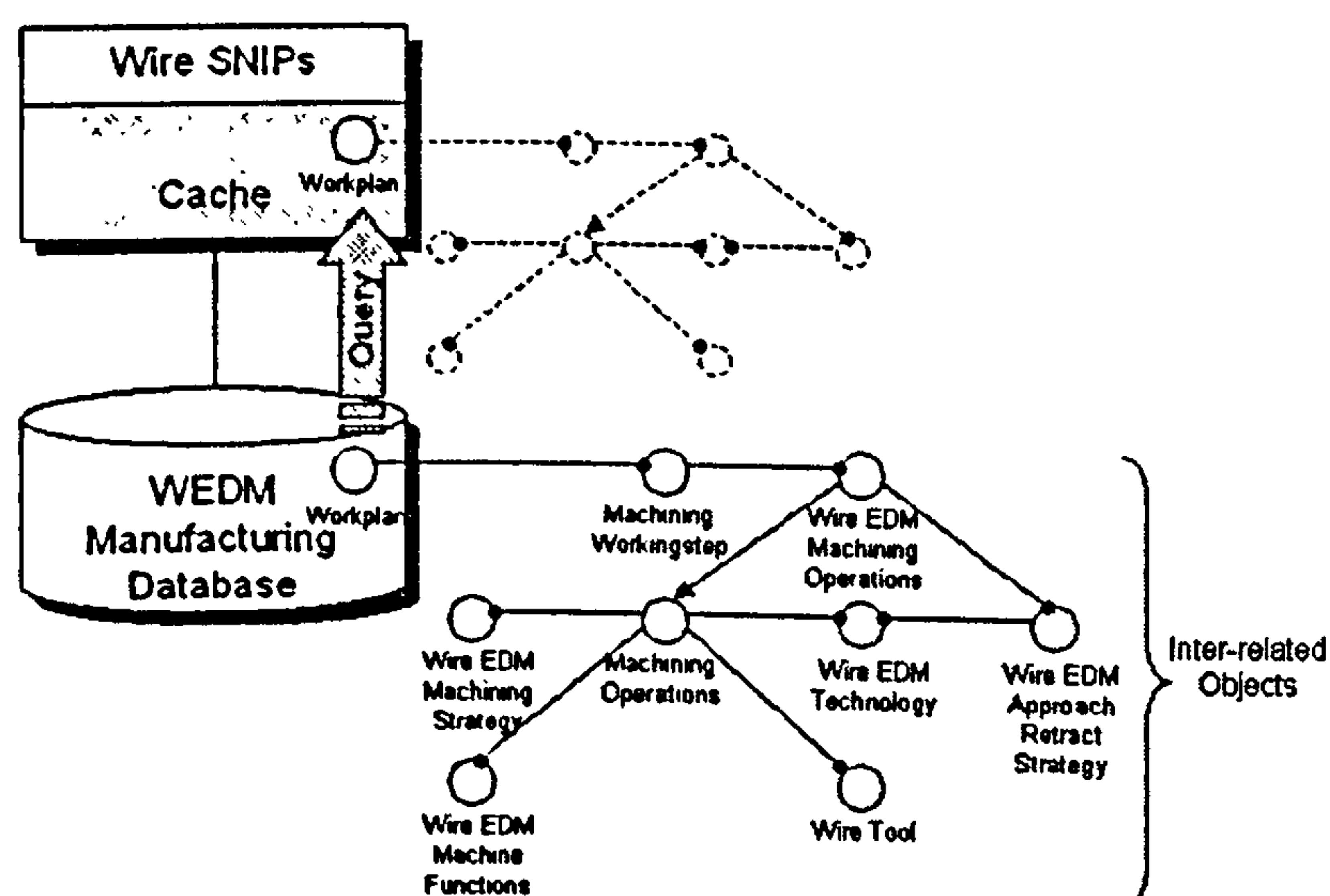


Figure 7.4 The query of the object-oriented Wire SNIPs database

The object-oriented ObjectStore DBMS has been applied to Wire SNIPs to perform the functions of data storage and retrieval. Its main merits included:

- Extensive improvement on object serialisation by providing the capability to read and write a smaller subset of the complete tree of objects at a time.



- Real-time responsive update/access to the locally cached data, especially if an application required updating/accessing the objects frequently.
- Coordinated multiple threads sharing a single database and protecting the integrity of data.
- Comprehensive library of Object Managers supporting multimedia applications by maintaining the data independent of the data types such as image, audio, full text, video or HTML.
- Native support for Java and C++ object models by managing the ObjectStore objects in a component-ready form.

The ObjectStore DBMS has been successfully adopted within the telecommunication market, however the growth of ebusiness has broadened its appeal to include ebusiness companies, financial institutions, and the embedded software market.

#### *7.2.4 Developing Wire SNIPs application*

The Java programming language has been employed to develop the Wire SNIPs applications. Its most appealing feature is the availability of the Java virtual machine (JVM) on almost all types of hardware and software, enabling Java applications to execute completely independent of the operating systems. JVM is a platform-independent runtime environment that converts java bytecodes into machine language and executes it. Therefore, such a 'write once, run anywhere' capability was expected to facilitate the Java applications written for Wire SNIPs to port easily between different platforms. Moreover, Java has a standardised support maintained and controlled by a single company, Sun Microsystems (2005), which supplies a consistent range of Java compilers and development environments. On the other hand, object-oriented programming languages, such as C++, are managed by different developers producing their own versions. Such a lack of a standardised support especially in the area of implementing the client-server environments has prompted the use of Java for the development of Wire SNIPs.

The Java software development kit (SDK) has been used to write and execute the Java application for Wire SNIPs. It consists of a few basic development tools and libraries that have created the process planning application for the prototype system and also contained a set of useful utilities that have debugged and documented the Java source code. In addition, the Java SDK included the necessary application programming interface (API) that provides a



library of definitions describing how Java should communicate with the ObjectStore DBMS. The Java API to ObjectStore essentially contains classes of related functionality that were used to construct the graphical user interface (dialog), to access the databases and to identify the inputs to and outputs from the Wire SNIPs. Figure 7.5 shows some of the core dialogs that were used in Wire SNIPs to capture the product and manufacturing information from the system users. The Project dialog was the opening dialog and was linked to the Workpiece dialog acquiring the product data and the Workplan dialog obtaining the manufacturing data. The characteristics of these dialogs corresponded to the STEP-NC entities, in which the *project* is the top-level entity of the STEP-NC process plan indicating the *workpiece* upon which the *workplan* was to be performed. Such as clear distinction of the dialogs was to facilitate the eventual storing of the data captured from the Workpiece and the Workplan dialogs into the product and manufacturing databases respectively.

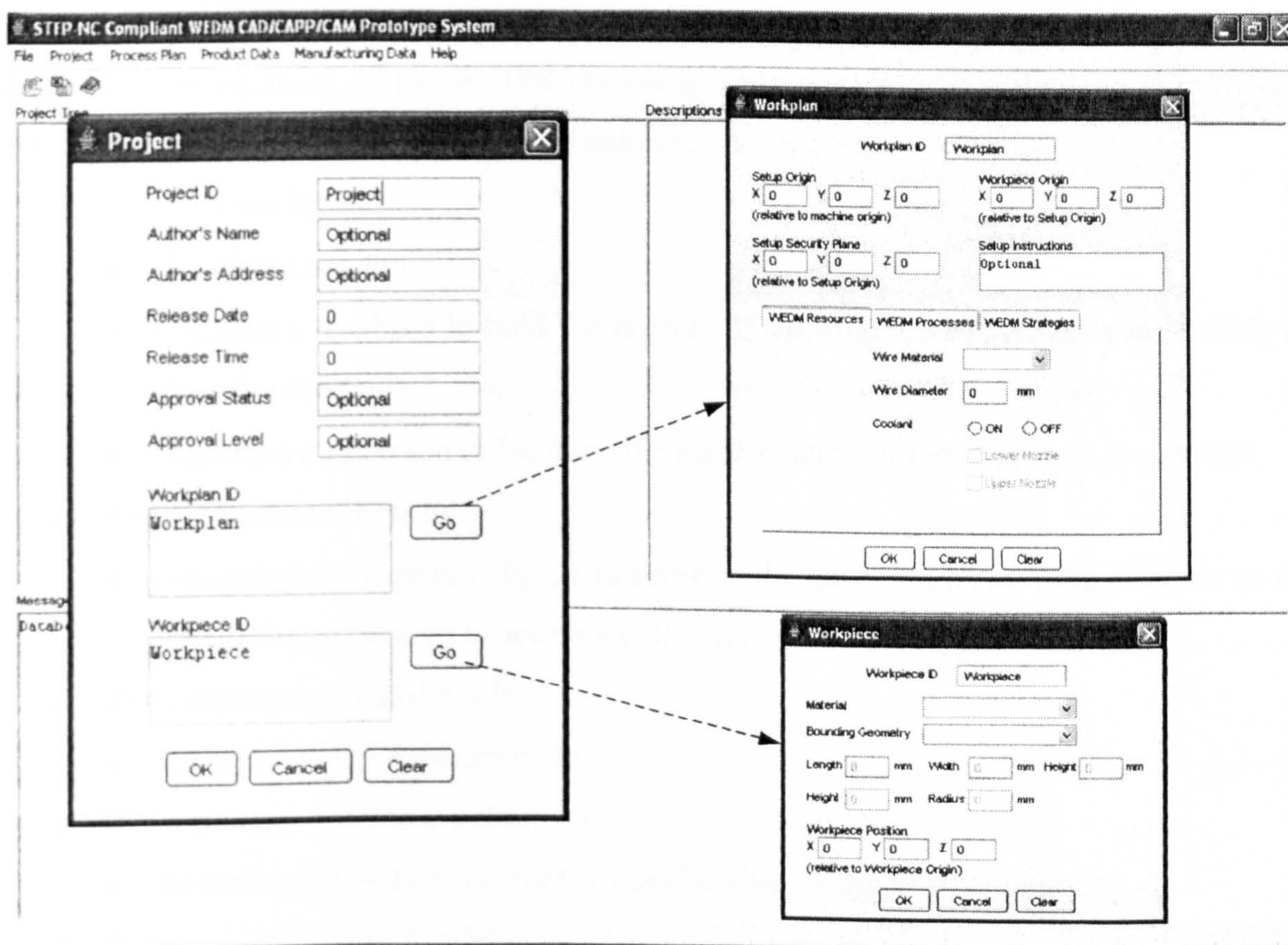


Figure 7.5 Wire SNIPs graphical user interfaces

Some of the commercial applications of Java include its use as a middleware to communicate between clients and server resources, such as the access to database. Its highly versatile language, through the use of SDK, is also making significant inroads in embedded systems such as hand-held devices and car computers. Hence, Wire SNIPs was expected to be



portable and executable on any third party implementations, such as web browsers or device-specific virtual machines.

### 7.3 Functional structure of Wire SNIPs

This section describes the two main functionalities of Wire SNIPs, which include managing the databases and planning the WEDM process.

#### 7.3.1 *Managing Wire SNIPs databases*

Wire SNIPs databases consist of the product database concentrating on the information about the product design, and the manufacturing database focusing on the information about WEDM manufacturing capability. Both the databases have been developed in ISO 14649, which are consistent with Lee and Bang (2003), who have argued that the standard can be used as a database for machining data, which has all the data of CAD/CAM and CNC systems. The instances of the WEDM classes or objects were manipulated in Wire SNIPs databases by performing the following operations:

##### *a. Start session by*

- Creating a session
- Creating a database to hold the objects or opening a database to read, modify or store the objects
- Starting a transaction to facilitate the manipulation of the objects in the session

##### *b. Create database roots by*

- Assigning the required objects to serve as the entry points into the database or the navigation references to access a collection of related objects

##### *c. Store objects in a database by*

- Referring to the database roots

##### *d. Retrieve objects in the database by*

- Referring to the database roots or performing an associative query

##### *e. Delete objects in the database by*

- Disconnecting the unwanted objects from their relationships
- Destroying the unwanted objects



*f. End session by*

- Committing the transaction to execute the logical unit of work
- Closing the database
- Terminating the session

However, the ObjectStore class files have to be compiled and post-processed before it can be executed in the Wire SNIPs application. This was because the ObjectStore DBMS required the object to be made persistent capable before an application could store that object in the database. The term persistent capable refers to the capacity of an object to be stored in a database (ObjectStore 2003). The post-processor added a few lines of code in the class files allowing the ObjectStore DBMS to recognise the state of these objects.

### 7.3.2 Planning WEDM process

The information manipulation operatives of Wire SNIPs were based on the IDEF0 diagrams illustrated in figure 5.3 and figure 5.4. It followed a hierarchical structure of generating a feasible STEP-NC process plan according to the different information describing the manufacturing capabilities of the WEDM process. During the initial stage of process planning, the *machining\_features* were to be recognised and a set of *wire\_edm\_machining\_operations* was to be determined for each feature by using a rule-based reasoning tool considering feature types, geometric information and tolerance. As this was not the primary aim of the research, the activity was assumed to have been carried out and the essential product information was assumed to have been stored in the product database. However, the remaining product information relating to the WEDM component was captured from the system users. This was carried out through the Workpiece dialog capturing the relevant STEP-NC entities related to the characteristics of the workpiece such as the *material* and *bounding\_geometry\_select* (shape and size of the workpiece).

Wire SNIPs mainly focused on the planning of the WEDM machining operation and the generation of the STEP-NC process plan. Figure 7.6 shows the how the resources, processes and strategies instances of the WEDM MModel facilitated the planning of the STEP-NC compliant WEDM machining operation. The typical planning activities included specifying the various STEP-NC entities associated with the characteristics of the WEDM machining operation such as the *wire\_tool*, *wire\_edm\_machine\_functions*, *workpiece\_setup*, *wire\_edm\_machining\_operations*, *wire\_edm\_machining\_strategy*, *wire\_edm\_technology* and



*wire\_edm\_approach\_retract\_strategy*. The planning of the WEDM machining operation also concentrated on:

- Determining the *workingsteps* based on the desired surface quality and the required number of cuts,
- Including additional *workingsteps* for the *cut\_through* and the *slug\_removal* operations,
- Identifying the machining precedence relations between operations in terms of the cutting modes such as roughing, finishing and surface finishing,
- Storing the product and manufacturing information in the respective product and manufacturing databases, and
- Facilitating the generation of the STEP-NC process plan.

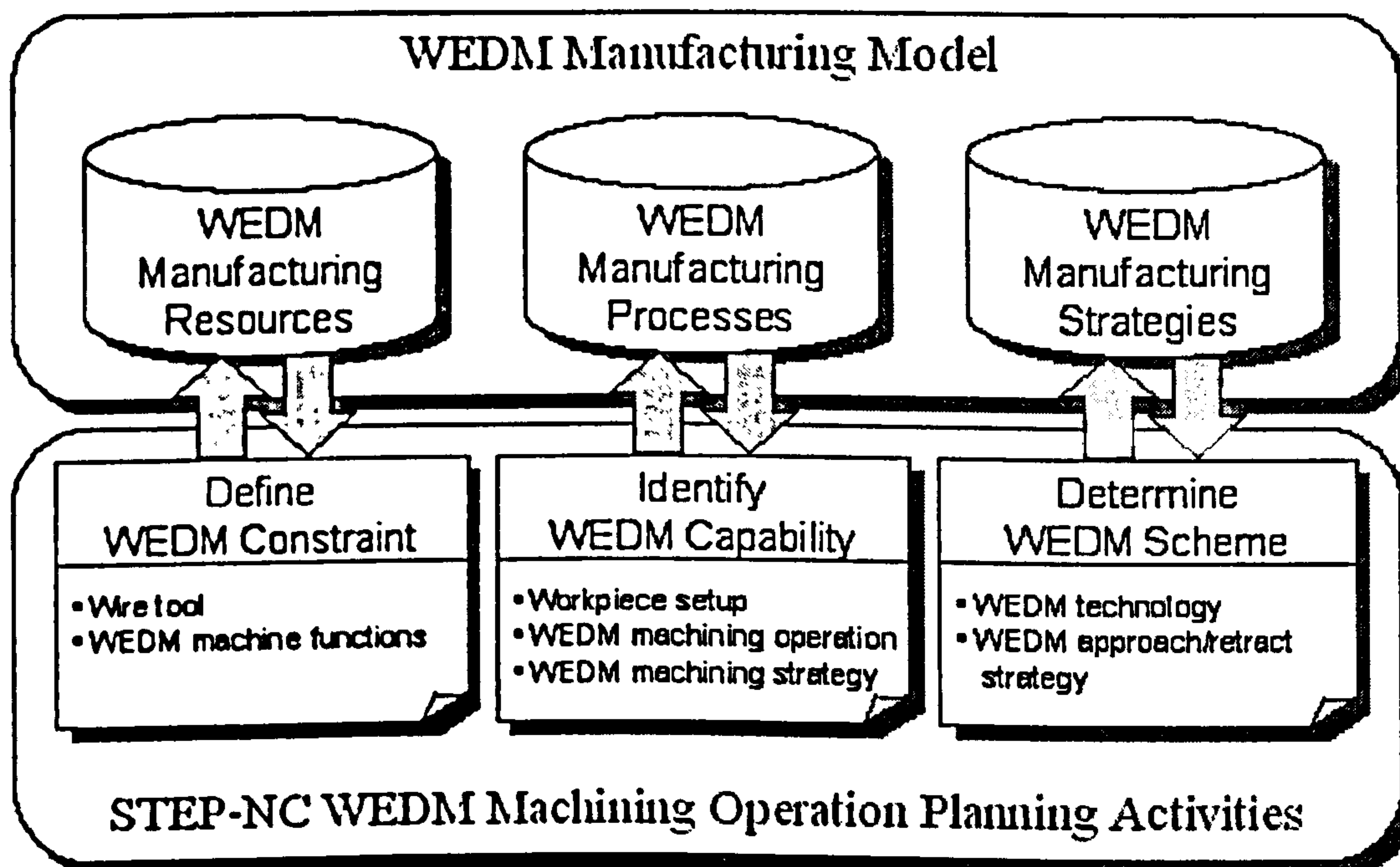


Figure 7.6 STEP-NC WEDM machining operation planning activities

In addition to the above-mentioned declarative knowledge captured from the system users, Wire SNIPs has provided the procedural knowledge required to plan the WEDM machining process. The declarative knowledge explicitly represents the WEDM process information whereas the procedural knowledge implicitly represents the WEDM process information through rules, expressions and equations that infer process capabilities from the input parameters (Giachetti 1999). As for the Wire SNIPs, it has particularly made use of the machining process logic and rules to define how the strategic decisions are reinforced and achieved.



The decision-making logic and rules developed within Wire SNIPs were limited to pre-defining the *workingsteps*. This logic and rules perform logical reasoning and deduce new knowledge by applying rules to facts so that process planning decisions can be made. One of the crucial logic and rules included determining the machining sequences without violating the machining precedence relations between machining operations. As each *workingsteps* only requires one *wire\_edm\_machining\_operation* for machining a feature on a component, the logic of operation followed a sequential order, which was roughing, finishing then surface finishing. The rules for sequencing these machining operations are based on the technological constraint of the WEDM machine, such as the number of cuts to achieve the required surface finishing quality. Different WEDM machine vendors have different sets of performance measures, e.g. one machine may require three cuts to achieve the specified surface finishing but another machine may be able to do it with just two cuts. However, the Wire SNIPs has assumed such machining characteristics, which are outside the scope of this research. Thus, Wire SNIPs has been constructed to perform all the three machining modes based on an example part, which could be found in the ISO/DIS 14649-13.

## 7.4 Operational structure of Wire SNIPs

This section describes the operational structure of the Wire SNIPs by identifying the programming procedure to generate the STEP-NC process plan for WEDM manufacturing.

### 7.4.1 Programming procedure of Wire SNIPs

The programming procedures on using the Wire SNIPs has been based on the system framework identified in chapter 5. It mainly sought inputs from the system users via dialogs, which were displayed according to the WEDM information models, as described in section 7.2.4. The Project dialog was the first dialog that appears on the screen each time a new project is created. Figure 7.7 shows the Project dialog, which serves as a starting point of the data-input process, which was basically mapped from the STEP-NC *project* entity. From this dialog, the system users are linked to the Workpiece dialog describing the attributes of the *workpiece* entity and the Workplan dialog describing the characteristics of the WEDM constraints, the WEDM capability and the WEDM schema.



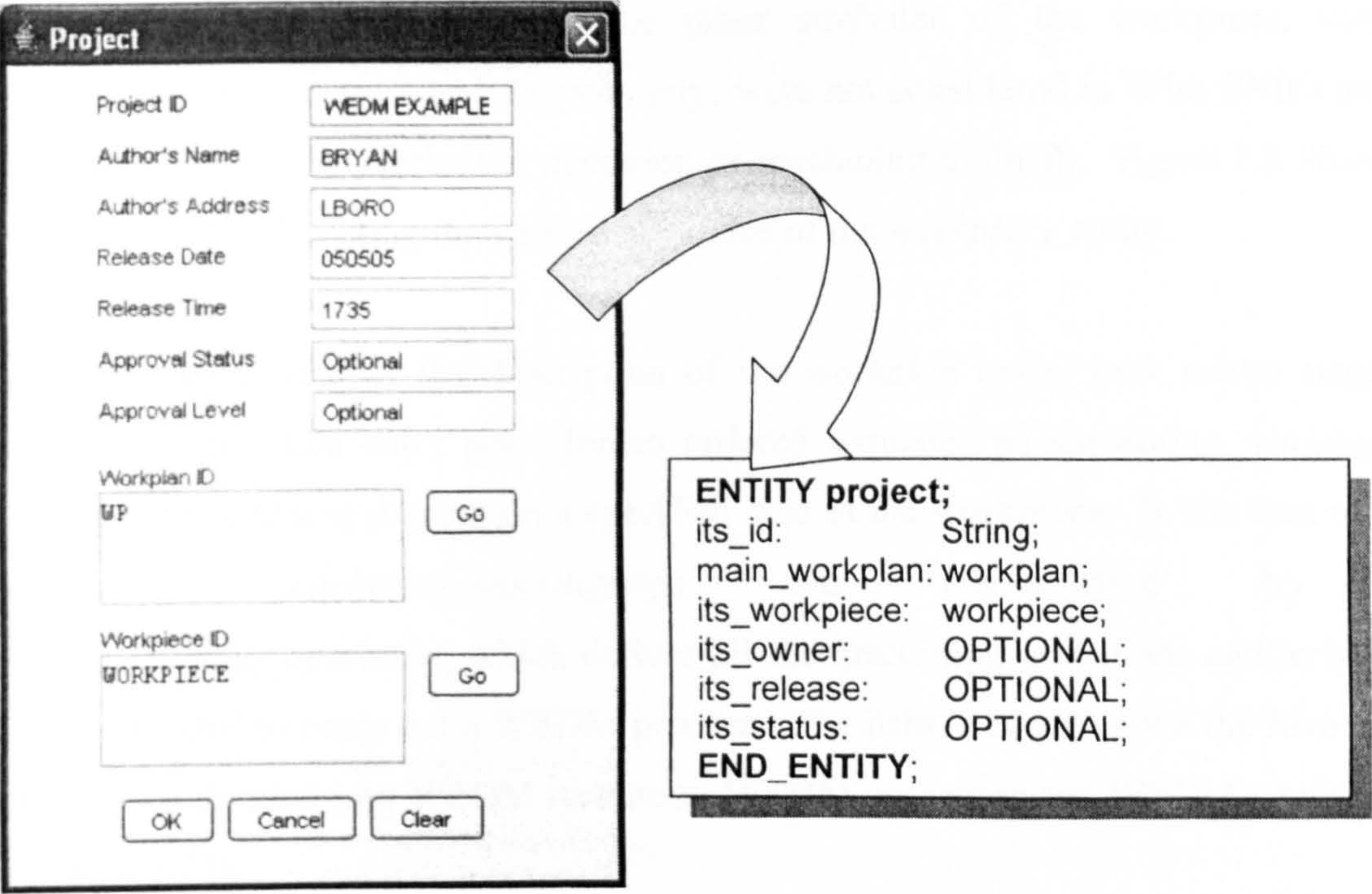


Figure 7.7 Wire SNIPs project dialog depicting the STEP-NC *project* entity

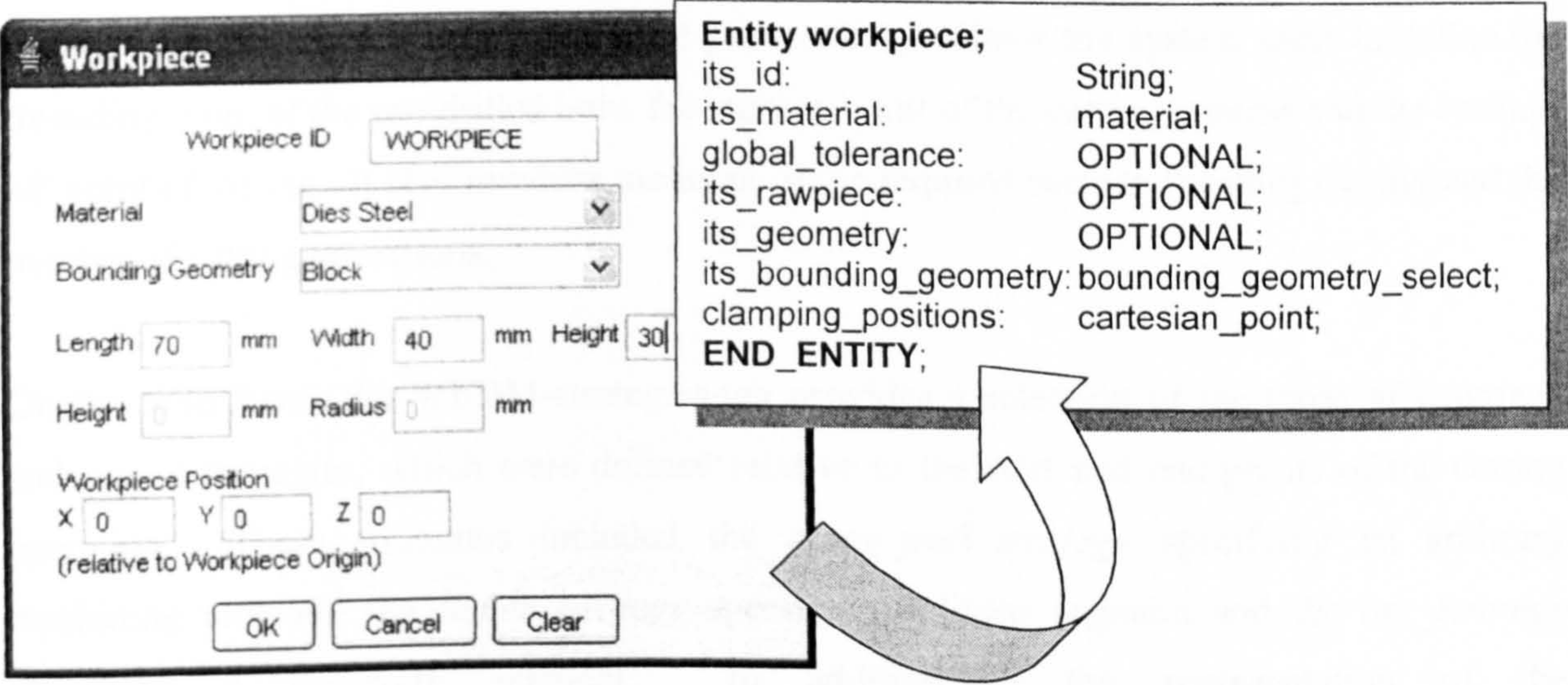


Figure 7.8 Wire SNIPs workpiece dialog depicting the STEP-NC *workpiece* entity

The relevant attributes of the *workpiece* entity were captured in the Workpiece dialog. They included the material of workpiece, the shape and size of workpiece, and the location of feature coordinate system relative to the workpiece origin. Most of the attributes were featured in a Java combo-box, which aids the system users in selecting the various options. For example, the attributes of the *bounding\_geometry\_select*, which described the bounding geometry of the workpiece as a *block* or a *right\_circular\_cylinder*, are displayed inside the



combo-box in a pull-down fashion. The other attributes of the workpiece, such as *global\_tolerance*, *its\_rawpiece* and *its\_geometry*, were not considered in Wire SNIPs as they have little/no effect on the machining operation or machining toolpath. Figure 7.8 illustrates the Workpiece dialog depicting the various attributes of the *workpiece* entity.

As for the Workplan dialog, the description of the *workplan* entity took centre stage. It mainly serves as the data entry point for an ordered sequence of *machining\_workingsteps* representing the machining process on a specified area of the workpiece. In the case of Wire SNIPs, the *machining\_workingsteps* are characterised by the *wire\_edm\_machining\_operation*, which defines all the machining operations and technology specific data needed to carry out a WEDM process. The data is captured via the Java tabbed pane, which was divided into WEDM resources, WEDM processes and WEDM strategies, as shown in figure 7.9.

The WEDM-resources-tab captures the description of the *wire\_tool* and the *wire\_edm\_machine\_functions*, which denotes the on/off state of the coolant to be applied during machining. Whereas, the WEDM-processes-tab allows the system users to define the threading point of the pre-drilled hole, the starting point of the cutting process and the cutting-off point of the tag. It also involves the input of the required surface finishing quality and the number of cutting operations.

On the other hand, the WEDM-strategies-tab provides a selection of the types of approach and retract strategies, which were defined relative to the start and end points of the cutting operation. These strategies included the *along\_path\_strategy* specifying an arbitrary machining toolpath, the *linear\_strategy* specifying a linear segment and the *arc\_strategy* specifying a linear-arc segment. In addition to the representation of the *machining\_workingsteps*, the Workplan dialog also considered the locations of the setup and the workpiece coordinate systems. The former describes the location of the setup coordinate system relative to the machine coordinate system, while the latter describes the workpiece coordinate system relative to the setup coordinate system, referred in appendix IV.



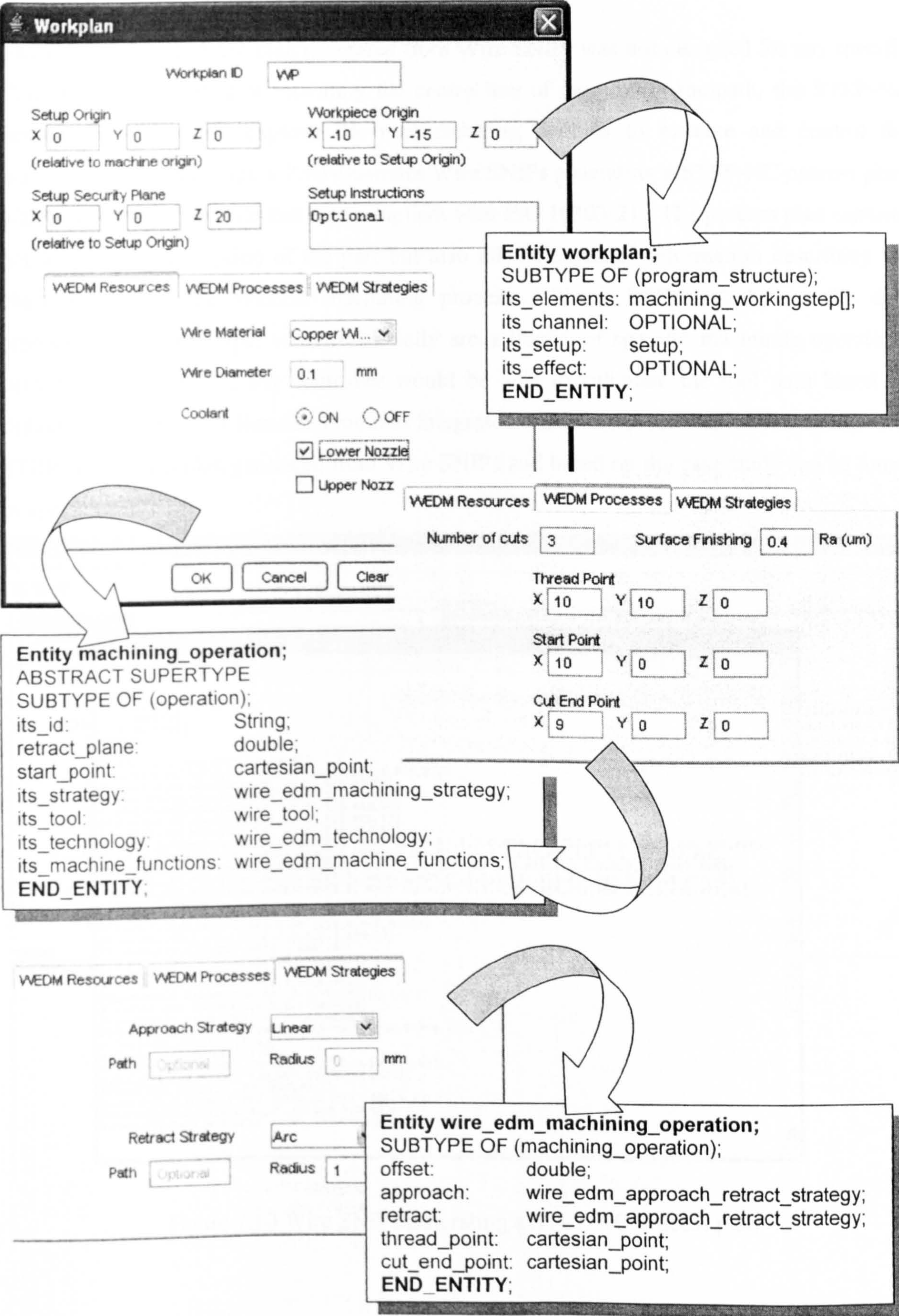


Figure 7.9 Wire SNIPs workplan dialog depicting the STEP-NC workplan, machining operation and wire edm machining operation entities



### 7.4.2 Generation of WEDM STEP-NC process plan

The format of the process plan generated from Wire SNIPs was not designed for any specific CNC machine. Instead of providing the centre line of the cutting toolpath, the STEP-NC neutral format directly exploits the manufacturing features to execute and control the machining operation. Figure 7.10 illustrates Wire SNIPs generating a STEP-NC process plan, which is actually a text file that was compliant with ISO 10303-21. The process plan captures not only a full description of the part but also all the essential information describing the characteristics of the WEDM machining process. Since, STEP-NC defines the data representing *workingsteps*, which essentially are a library of specific machining operations performed at the CNC, any controller would be able to calculate the tool path based on definitions contained in formatted routines integrated within the controller (Lewis 2002). The STEP-NC process plan generated from Wire SNIPs and based on the case study can be found in appendix II.

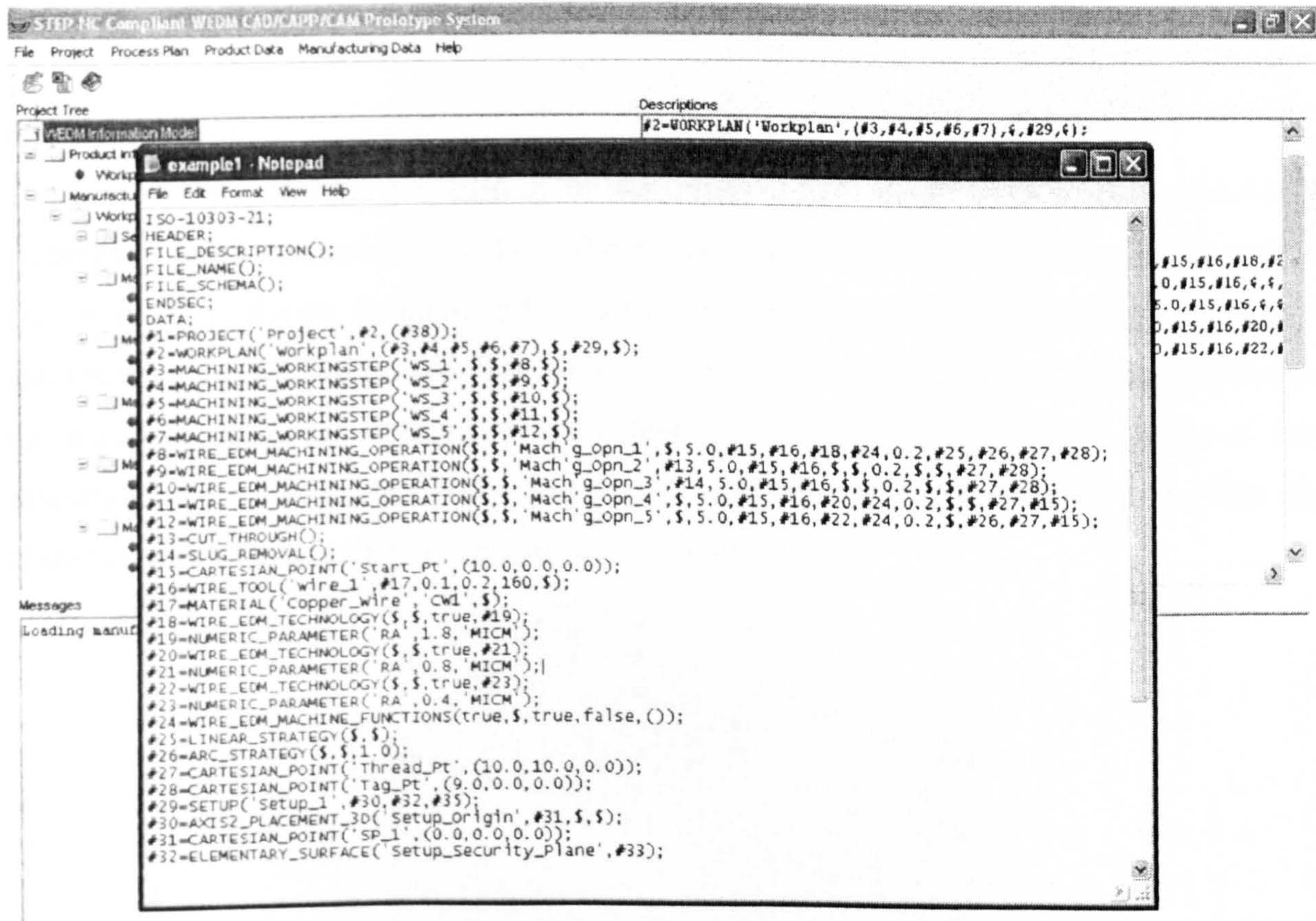


Figure 7.10 Wire SNIPs generating a STEP-NC process plan



# Chapter 8

## CASE STUDY, TESTING & RESULTS

### 8.1 Introduction

This chapter describes the testing of Wire SNIPs through the use of the example case study found in ISO/DIS 14649-13. It also forms the basis of critically evaluating the author's STEP-NC compliant WEDM information models driving the Wire SNIPs. The evaluation has been carried out by comparing the information residing in these WEDM information models with the ISO 6983 based information that has been supplied to the two commercial WEDM CAD/CAM systems. These systems include the PEPS Solid Cut Wire EDM together with the PC FAPT Cut i and have been benchmarked in terms of the programming procedures and the programming/machining parameters in the evaluation.

### 8.2 Case study

The first WEDM example part used in the case study is from the STEP-NC standard and is a rectangular block measuring 70 x 40 x 30 mm. It requires the machining of a 20 mm square die opening, as shown in figure 8.1. The machining of a die opening, which is widely machined by the WEDM process, has been used as the case study. It is commonly required in the machining of most mechanical and automotive parts. Table 8.1 shows some of the essential properties of the WEDM example part 1 and the wire tool together with the relevant characteristics of machining the 20 mm square die opening.

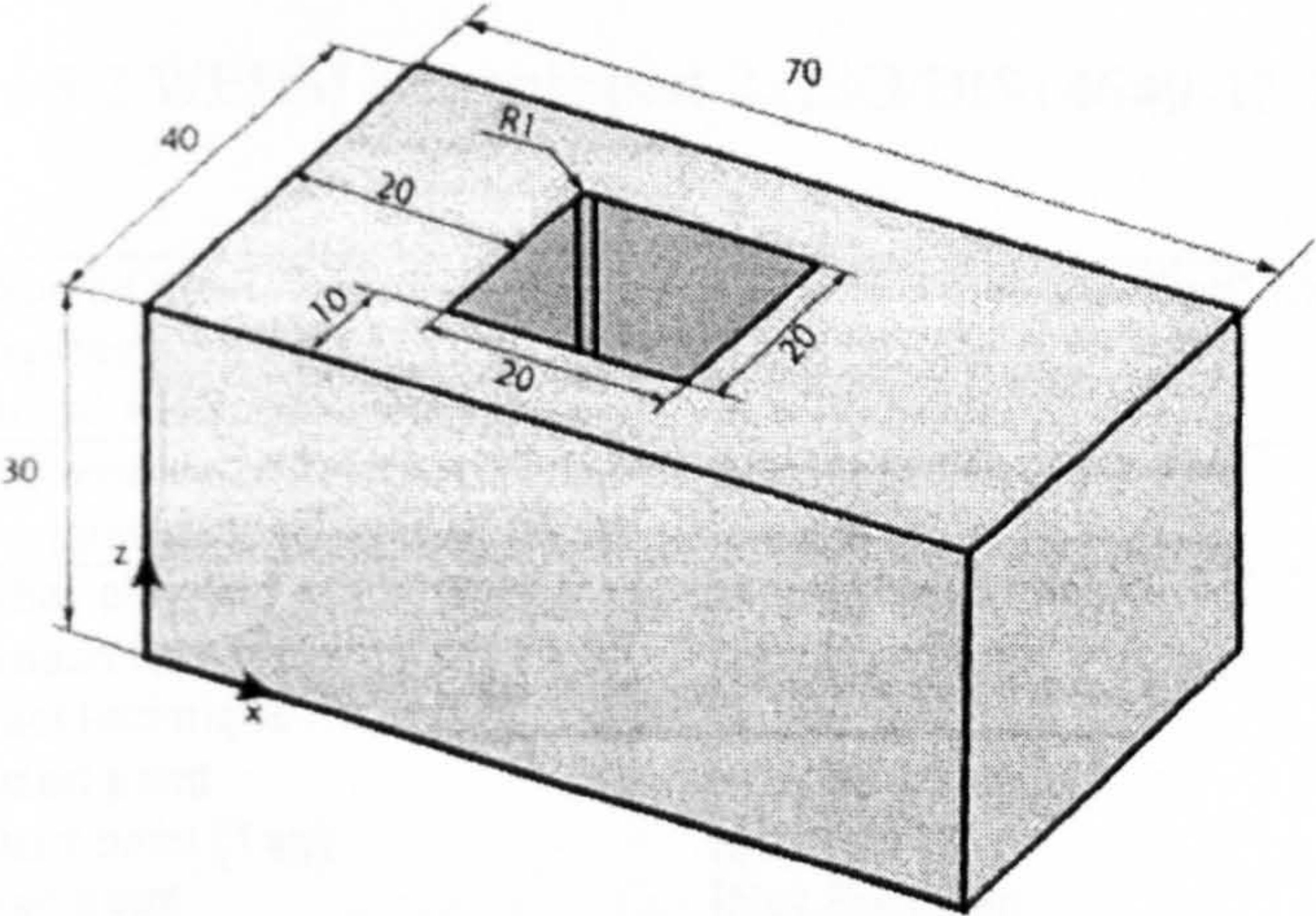


Figure 8.1 WEDM example part 1 (ISO/DIS14649-13 2003)



Workpiece size	70 x 40 x 30 mm
Workpiece material	ST221 Cold Die Steel
Required surface finishing quality	Ra 0.4 µm
Wire diameter	0.1 mm
Wire material	ST234 Cobra Cut A
Number of cuts	1 roughing, 1 finishing, 1 surface-finishing
Approach technique	Linear (roughing)
Retract technique	Linear (roughing), Arc of radius 1 mm (surface-finishing)
Cut start point	10,0,0
Cut end point (Tag)	9,0,0
Thread point	10,10,0
Coolant	On
Upper nozzle	Off
Lower nozzle	On

Table 8.1 Machining characteristics of the WEDM example part 1

The second example part also requires the machining of a die opening with inclined surface, as shown in figure 8.2 and table 8.2. The STEP-NC process plans for machining these two WEDM example parts can be found in appendix III and are mainly used to evaluate the performance of Wire SNIPs.

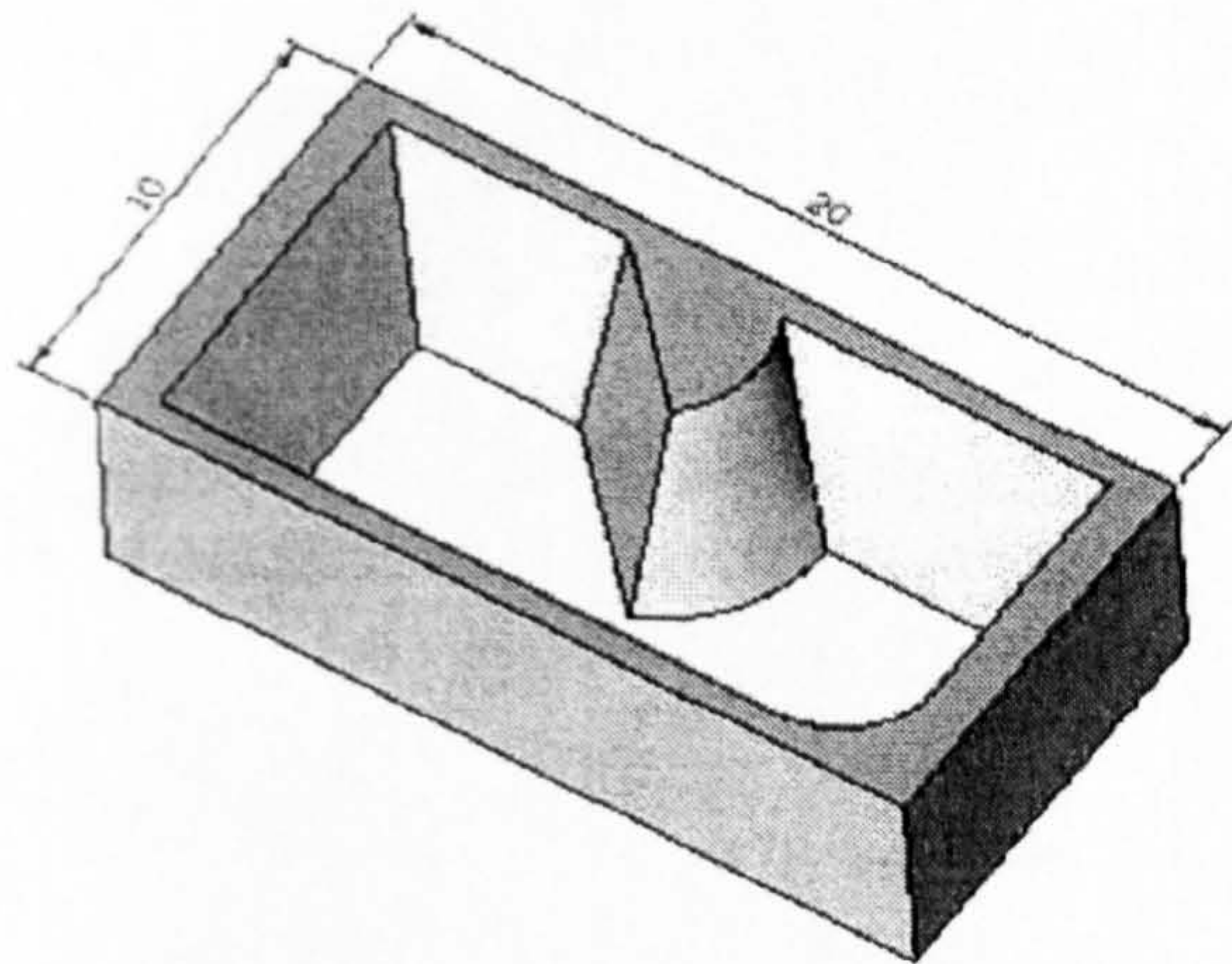


Figure 8.2 WEDM example part 2 (ISO/DIS14649-13 2003)

Workpiece size	20 x 10 x (not specified) mm
Workpiece material	Cold Die Steel
Required surface finishing quality	Ra 1.8 µm
Wire diameter	0.25 mm
Wire material	Cobra Cut
Number of cuts	1 roughing
Approach technique	Not Specified
Retract technique	Linear
Cut start point	Not Specified
Cut end point (Tag)	Not Specified
Thread point	Not Specified
Coolant	On
Upper nozzle	Off
Lower nozzle	Off

Table 8.2 Machining characteristics of the WEDM example part 2



### 8.3 Commercial WEDM CAD/CAM systems

The evaluation of the WEDM information models outlined in chapter 6 was supported by the use of two commercial WEDM CAD/CAM systems. One of the systems was the PEPS Solid Cut from Camtek Ltd (2005), which also designs, develops and markets a range of CAD/CAM software for the other CNC machining processes, such as milling, turning and laser cutting. PEPS Solid Cut operates on an integrated modular software platform facilitating the definition of the machining profile by means of the CAD system and the application of the machining parameters through the CAM system. The PEPS Solid Cut CAD system has a flexible translator interface supporting a number of industrial data transfer standards when importing CAD drawings and data models, such as IGES, AutoCAD DWG and STEP. Figure 8.3 illustrates a machining simulation of the WEDM example part 1 carried out by the PEPS Solid Cut.

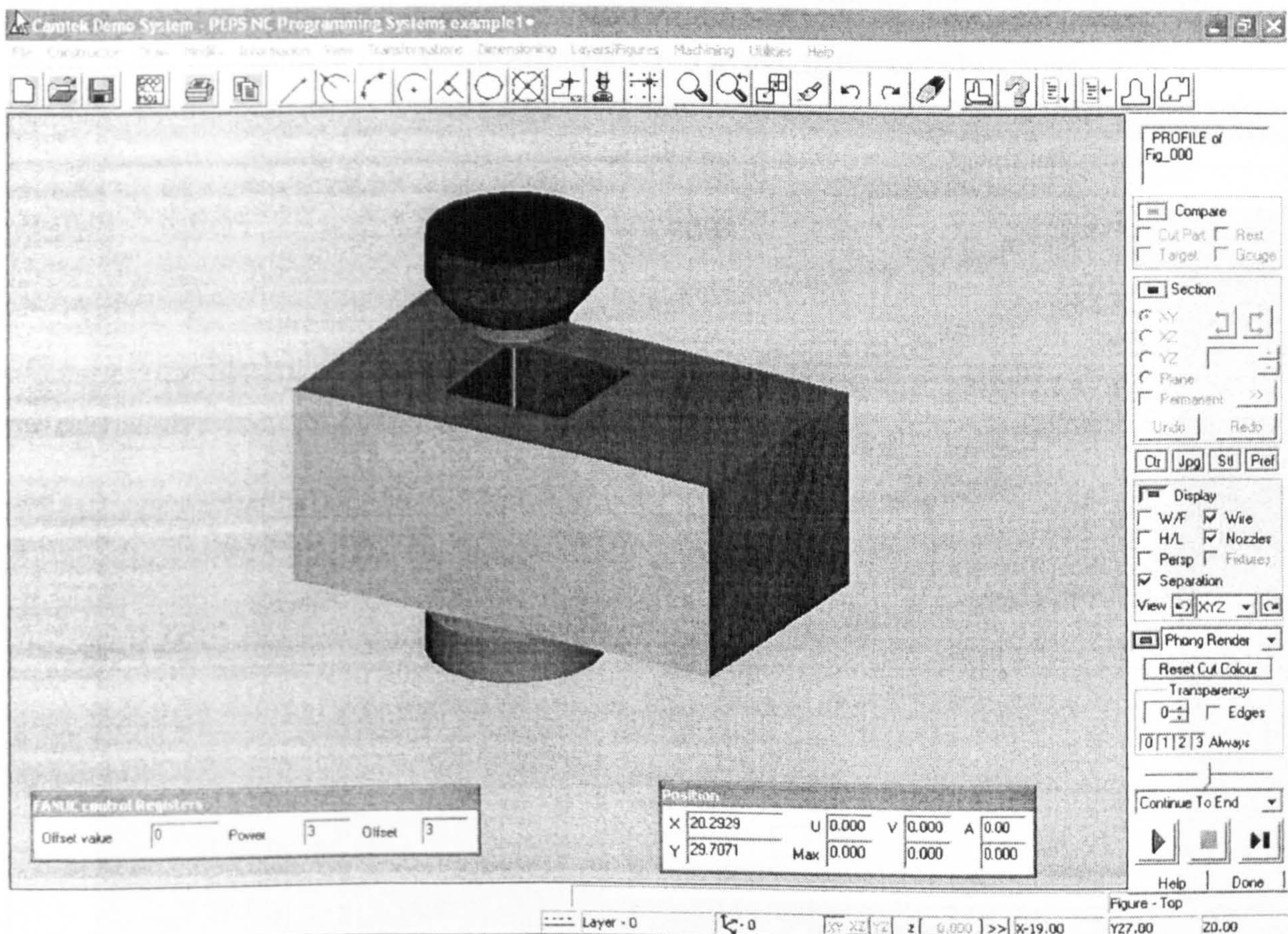


Figure 8.3 PEPS Solid Cut simulating the machining of the WEDM example part 1

PEPS Solid Cut has a set of post processors serving the need to generate a specific NC part program for the different WEDM machine controllers including the Agievision, Charmilles, Mitsubishi and Sodick controls. It is specially written as an offline-programming tool. The common applications of PEPS Solid Cut can be found in precision machining together with



tool and die making industries. These industries manufacture typical products such as cutting tools with different rake angles, cams and gears of complex profiles, and extrusion dies with variable land features.

FAPT was the second commercial WEDM CAD/CAM system used in the evaluation. It was obtained from 600 Centre (2005), which produces a wide variety of machine tools including the Fanuc Robocut WEDM machine. FAPT is exclusively dedicated to the Robocut machine, which is recognised for establishing the first automatic wire threading system using the annealing and thermal cut off technique. In addition to the standard CAD and CAM features, FAPT has various types of intelligent cutting control functions that enable the Robocut machine to yield an optimum machining process. These intelligent functions together with the adaptive control software facilitates the selection and adjustment of the cutting conditions according to the changes in workpiece thickness and the cutting types such as corners and tapers, while maintaining the cutting efficiency and avoiding the wire breakage.

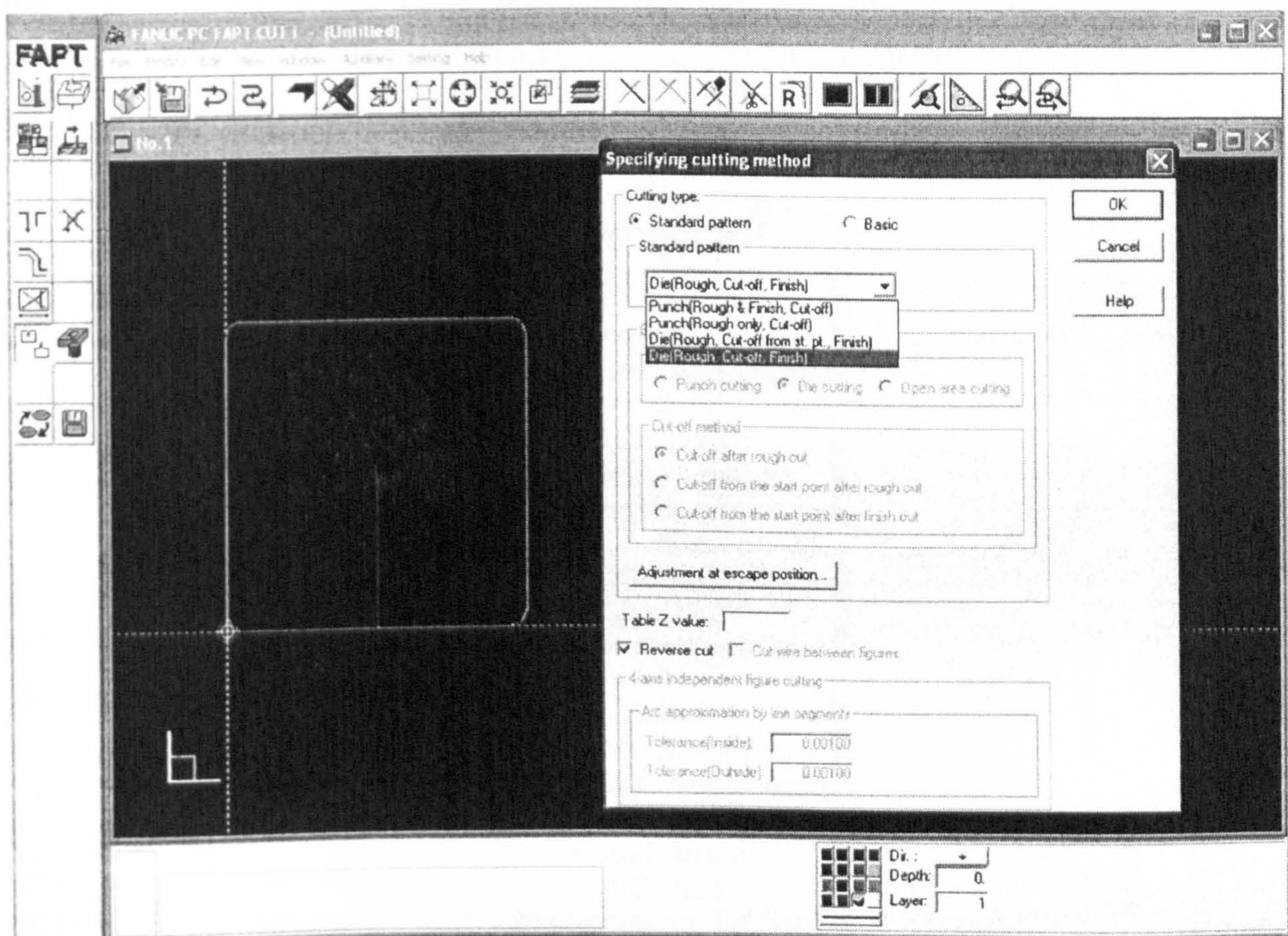


Figure 8.4 FAPT programming the machining setup for the WEDM example part 1

In addition, FAPT has several machining routines, which promote higher machining productivity when cutting multiple profiles on a single workpiece by maximizing the



unattended operation of the machine, as shown in figure 8.4. The programming on FAPT was commonly performed off-line, which only requires the system user to enter the details of the cutting profile, size of workpiece, material, wire size and the number of roughing and finishing cuts. It is often put to effective use in producing punch and cut-off dies and is capable of handling the machining using a wire diameter as small as 0.05 mm.

#### 8.4 Basis of evaluating Wire SNIPs

The basis of evaluating Wire SNIPs has been carried out by examining the programming procedures and the part program of PEPS Solid Cut and FAPT and is outlined below.

##### 8.4.1 PEPS Solid Cut and FAPT programming procedures

The general procedures for producing a NC part program using PEPS Solid Cut and FAPT could be broken down into 5 stages. It consists of creating/importing the machining profile, translating the profile into a machining toolpath, determining the machining operations, selecting the cutting conditions and post-processing the NC data into a controller-specific part program, as shown in figure 8.5.

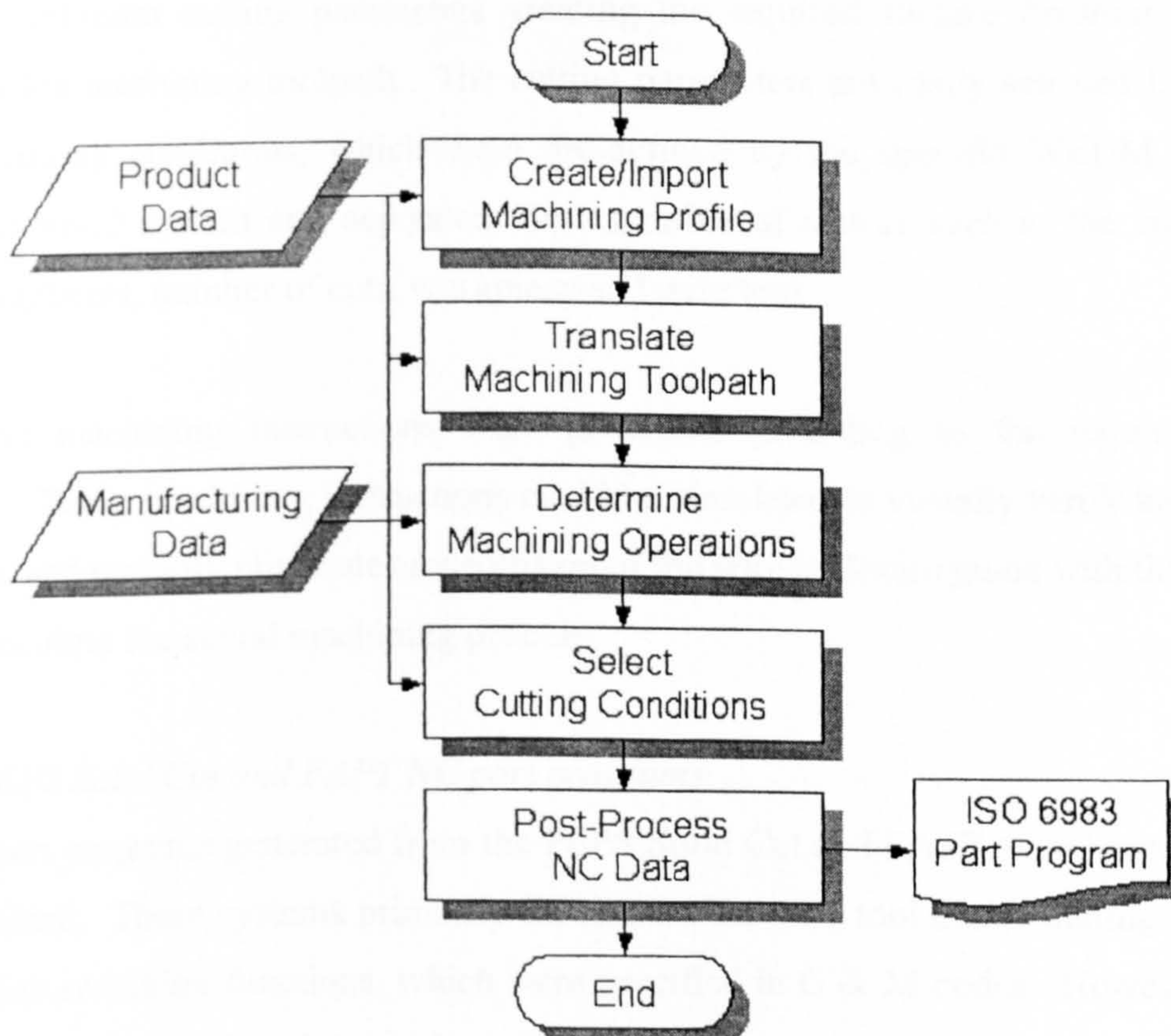


Figure 8.5 General programming procedure of commercial WEDM CAD/CAM system based on ISO 6983 standard



The first stage is mainly concerned with the definition of the part geometries, which can be either created by using the existing CAD drawing tools or imported from other CAD packages. It also requires the details of workpiece, which assist in the subsequent graphical simulation of the machining process. The second stage involves the translation of the part geometries into wire tool centre cutting location allowing the machine controller to identify the starting and leading points. For the example parts, the starting point is the location where the wire threaded through a pre-drilled hole in the workpiece, whereas the leading point provides the location for the wire to feed into the machining toolpath. More importantly, this stage ensures that there are no breaks in the machining toolpath.

The third stage focuses on determining the type of machining functions and machining routines to be used on the selected WEDM machine. These machining functions include the automatic wire threading system and intelligent cutting control functions, while the machining routines specify the basic cutting mode, cut-off type, cutting direction, and approach/retract strategy according to the types of WEDM parts, as shown in figure 6.6.

Next, the optimum cutting parameters yielding the required surface finishing quality are applied to the machining toolpath. The cutting parameters are easily selected from a set of standard cutting conditions, which were pre-defined by the specific WEDM CAD/CAM knowledge-based system and dependent on a number of factors such as the cutting speed, surface roughness, number of cuts, workpiece and wire tool.

Lastly, the machining instructions were generated according to the required machine controller. These machining instructions could be simulated to visually verify the machining operations and possibly eliminate any collision of the wire tool/wire guide with the setup tools before executing the actual machining process.

#### *8.4.2 PEPS Solid Cut and FAPT NC part programs*

The NC part programs generated from the PEPS Solid Cut and FAPT were based on the ISO 6983 standard. These systems primarily focused on the wire tool centre cutting motions and the machine switching functions, which were specified in G & M codes. However, different types of CNC required a dedicated post-processor in order to execute these codes giving instructions about the motions of the machine and the switching states of machine functions.



Figure 8.6 and 8.7 show the generation of a WEDM part program from PEPS Solid Cut for a Mitsubishi control and from FAPT for a Fanuc control respectively.

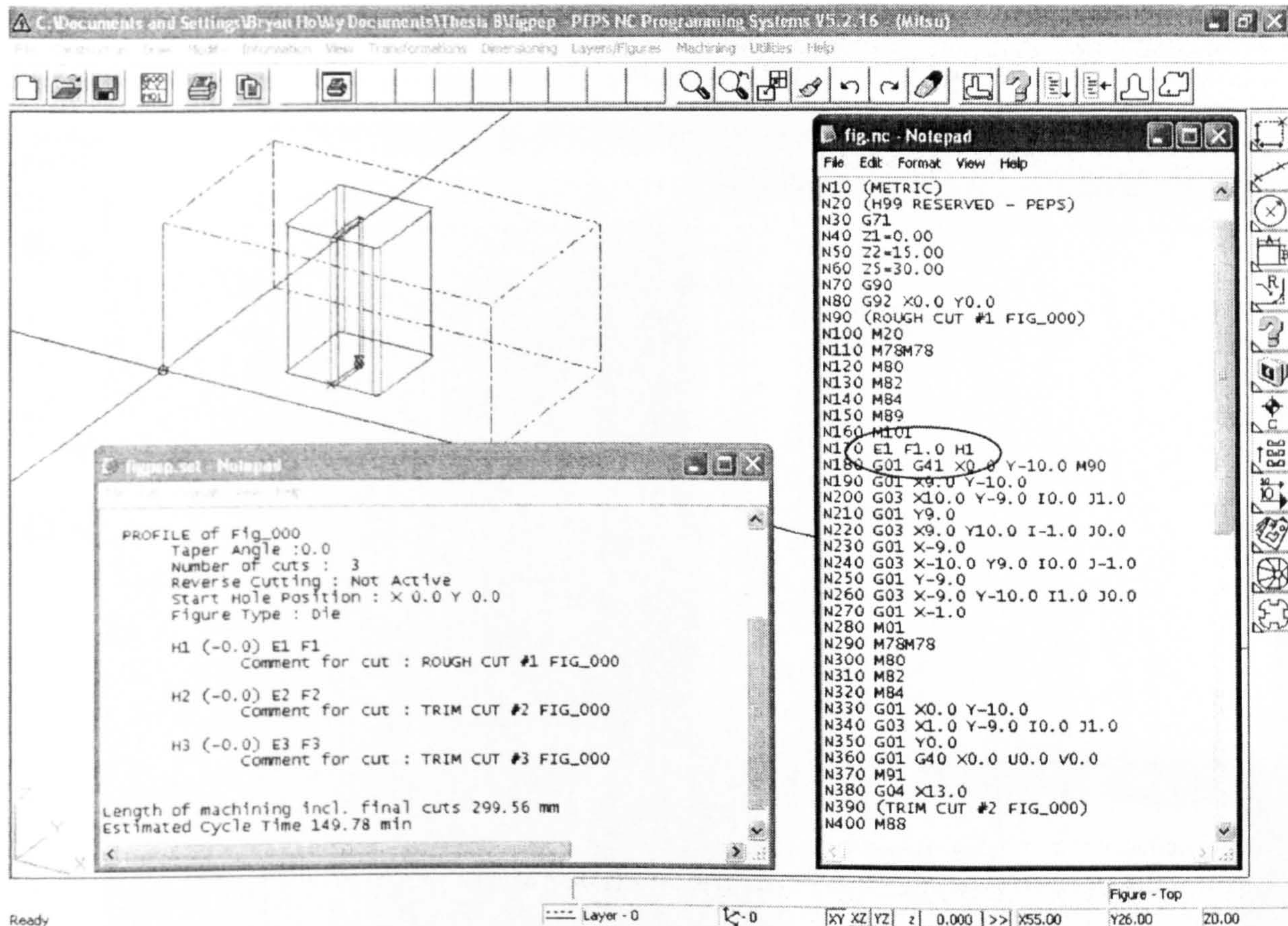


Figure 8.6 PEPS Solid Cut generating an ISO 6983 NC part program for example part 1 for Mitsubishi WEDM control

The machine-specific post-processor customised certain G & M codes in the ISO 6983 NC part program for a particular CNC vendor. It would define a unique code for a machining characteristic that was exclusive to a WEDM machine. For example, the G60 corner strategy and the G64 advanced offsetting were only available at the Charmilles machines (Camtek 2005). The former code changed the wire speed to maintain the finish quality on corners, whereas the latter code applied an offset parallel to the existing taper angle of the wire. In addition, the cutting conditions for the various WEDM CNCs were represented differently. For example, the cutting conditions reflected in the FAPT part program generated for the Fanuc control were represented as 'S1D1', which specified the condition number and the offset number, as shown in figure 8.7.

However, these cutting conditions are represented as 'E1F1H1' in the PEPS Solid Cut part program generated for the Mitsubishi control, as highlighted in figure 8.6. These NC part



programs, which are based on the same case study, can be found in appendix V. These ambiguities in the representation of the NC part programs for the different WEDM CNC vendors causes a major problem to the exchange of data and the interoperability of part programs when machining a component at different machine.

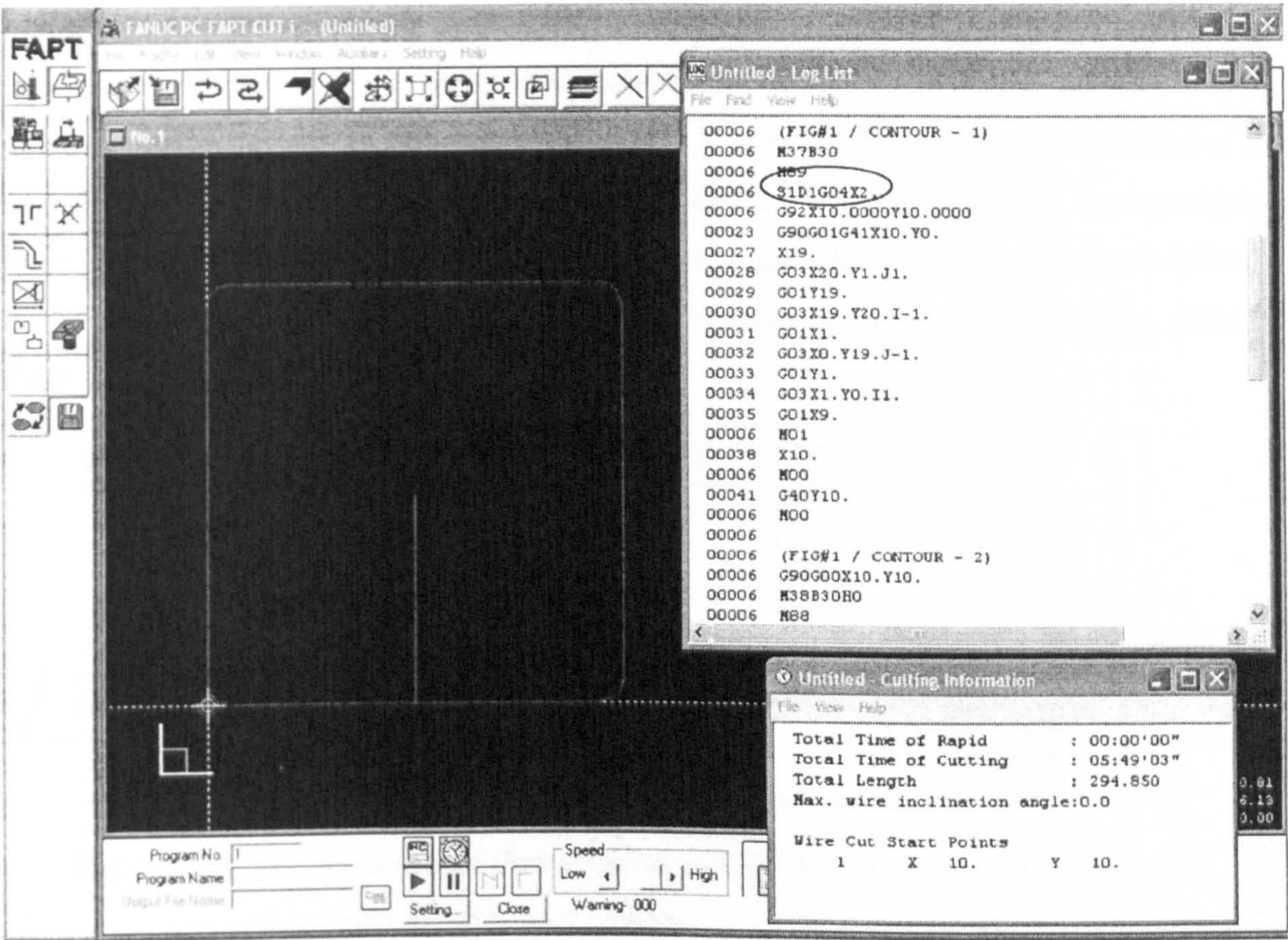


Figure 8.7 FAPT generating an ISO 6983 NC part program for example part 1 for Fanuc WEDM control

8.5 Test results

This section provides a comparison between the different NC part programs/STEP-NC process plan generated by the FAPT, PEPS Solid Cut and Wire SNIPs. The comparison is primarily based on the implementation of these NC part programs/STEP-NC process plans and the programming/machining parameters.

8.5.1 Directional flow of data

The PEPS Solid Cut and FAPT methods of generating a part program have an effect on the provision of the feedback among the different and otherwise incompatible computer platforms. These conventional methods restrict the flow of data to a top-down approach



making it difficult to modify or correct the final NC part program at the machine shopfloor without gaining a certain level of understanding of the G & M codes. Figure 8.8 shows the unidirectional data flow existing in the conventional method of generating an ISO 6983 part program. This effect could be traced to the CNC, which has no access to the product and process information residing in these CAD/CAM systems. Therefore, any major modification or correction to the NC part program could only be carried out by repeating the programming procedure and calculating a new cutting toolpath. Moreover, the ambiguous definition of the G & M codes provides the loopholes in accommodating and satisfying the new machining functionality, such as the Charmilles G60 and G64 codes. As such, it causes great difficulty in exchanging essential information about the machining process between the different CAD/CAM systems and CNCs.

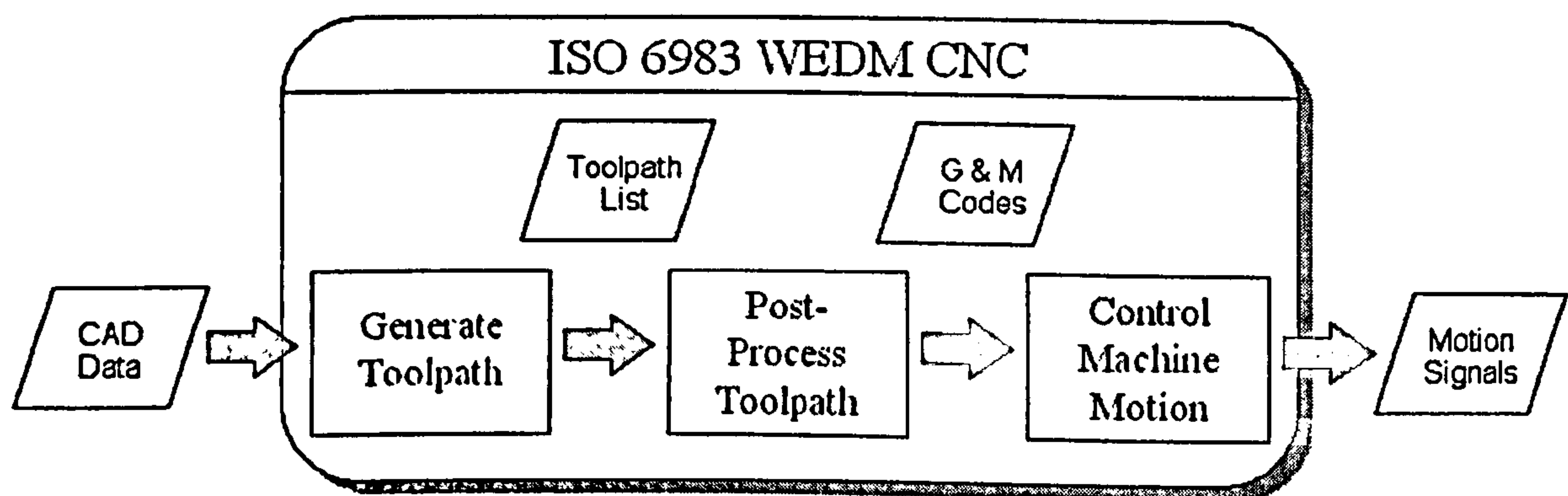


Figure 8.8 Unidirectional data flow presents in ISO 6983 part programming method

On the other hand, the Wire SNIPs method of generating a STEP-NC process plan provided a bi-directional flow of data. It does not require a separate toolpath file, post-processor and G & M codes in order to produce the neutral-format STEP-NC process plan, as shown in figure 8.9. The figure also shows how the Wire SNIPs process plan could be sent to a WEDM CNC for converting the machining instructions into specific machine codes through the use of the STEP-NC compiler.

Unlike the PEPS Solid Cut and FAPT NC part programs defining only the cutting motions, cutting conditions and cutting offsets, the Wire SNIPs process plan went beyond the information that the machine control required. Wire SNIPs provides an unambiguous and full coverage of the manufacturing process by specifying the wire tool, tolerances, set up, task plan and task execution, which were based on the STEP-NC standard.



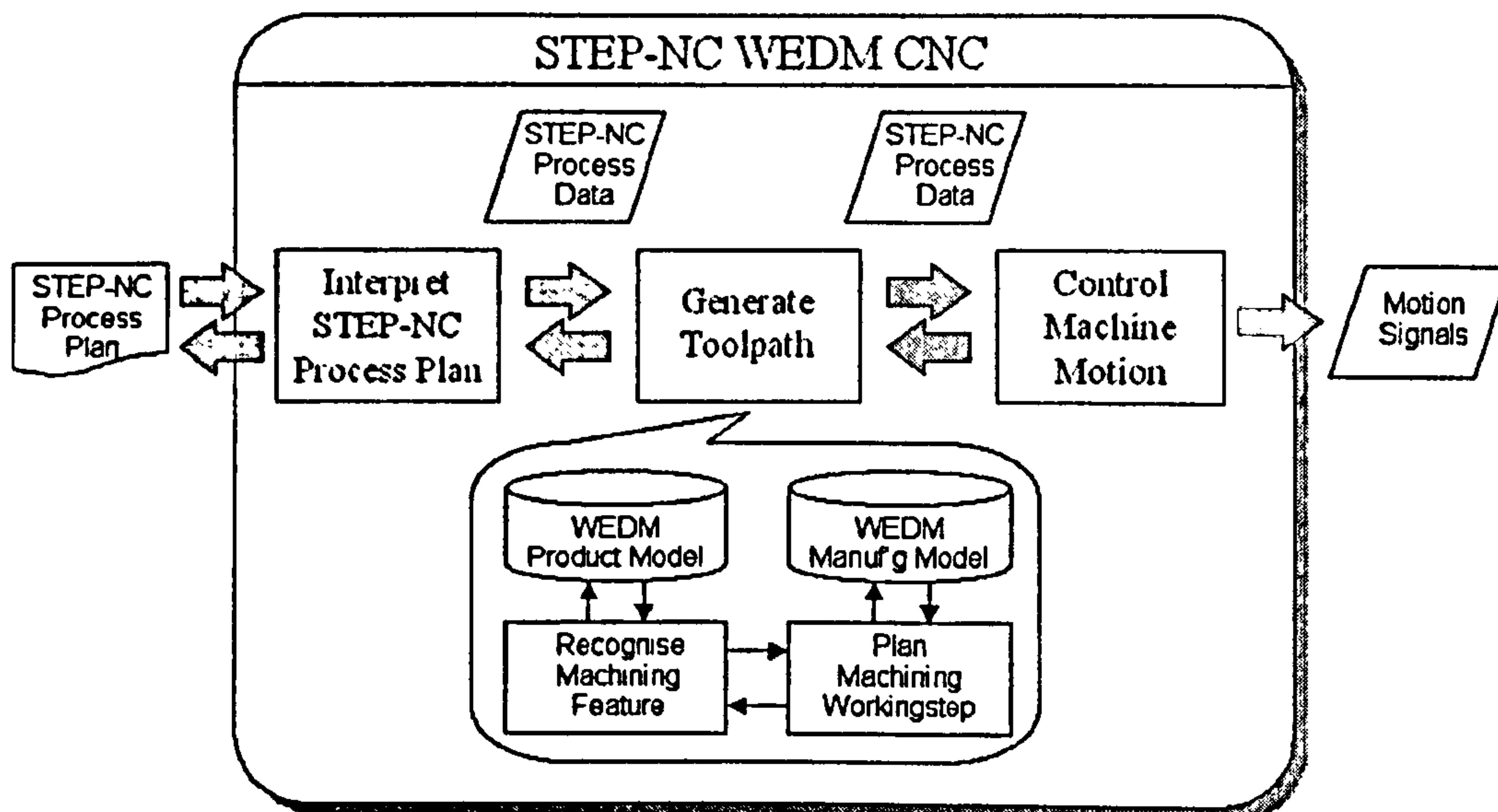


Figure 8.9 STEP-NC bi-directional flow of data

### 8.5.2 Programming/Machining parameters

The various programming or machining parameters needed to drive the PEPS Solid Cut, FAPT and Wire SNIPs have also been compared. The aim of such a comparison was to investigate the viability of the STEP-NC standard for the WEDM process. By doing so, it enabled the identification of the additional process data for the ISO/DIS 14649-13 standard in order to fully satisfy the various requirements of planning the WEDM process. Table 8.3 compares the STEP-NC entities used in Wire SNIPs against the programming characteristics utilised in the PEPS Solid Cut and FAPT.

The table shows that PEPS Solid Cut and FAPT did not pay particular attention to the definition of the workpiece and the wire tool, and focus mainly on the calculation of the cutting toolpath. The specification of the coolant has also been neglected largely due to the growing trend of conducting the WEDM machining process in a tank filled with deionised water instead of applying direct jet flushing near the sparking zone. Although, most of the PEPS Solid Cut and FAPT programming characteristics measured up to the STEP-NC entities, they were not reflected in their respective NC part programs.



STEP-NC Entity	STEP-NC Attributes	Wire SNIPs (ISO 14649-13)	PEPS Solid Cut (ISO 6983)	FAPT (ISO 6983)
Workpiece	Material	✓	✓	✓
	Tolerance	✓	x	x
	Rawpiece	✓	x	x
	Geometry	✓	x	x
	Shape and size	✓	✓	✓ (thickness only)
	Clamping position	✓	x	x
WEDM Machining Operation	Retract plane	✓	✓	✓
	Cut start/end point	✓	✓	✓
	Offset	✓	✓*	✓*
	Thread point	✓	✓	✓
WEDM Machining Strategy	Backmotion	✓	x	✓
	Cut-through	✓	✓	✓
	Slug-removal	✓	✓	✓
Wire Tool	Material	✓	✓	x
	Diameter	✓	✓	✓
	Tension	✓	x	x
	Speed	✓	x	x
WEDM Machining Functions	Coolant (on/off)	✓	x	x
	Pressure	✓	x	x
	Upper/Lower nozzle (on/off)	✓	x	x
WEDM Technology	Small corner strategy	✓	✓	✓
	Global/Local technology	✓	✓	✓
Wire EDM Approach/Retract Strategy	Along/Linear/Arc	✓	✓	✓

\* (punch/die/no-core cutting specific)

Table 8.3 Comparison between the PEPS Solid Cut, FAPT and Wire SNIPs programming/machining parameters

Table 8.4 shows the additional WEDM process data for the ISO/DIS 14649-13 standard. The author has listed these data against the appropriate WEDM STEP-NC entities. Some of this data has been described in section 6.4, the others include:

*Escape amount* – exists only when the cutting of the tag is performed at the very last stage, as illustrated in figure 8.10. It provides a means for the wire to approach/retract from the machining profile, thereby reducing the visible tag marks on the WEDM part.

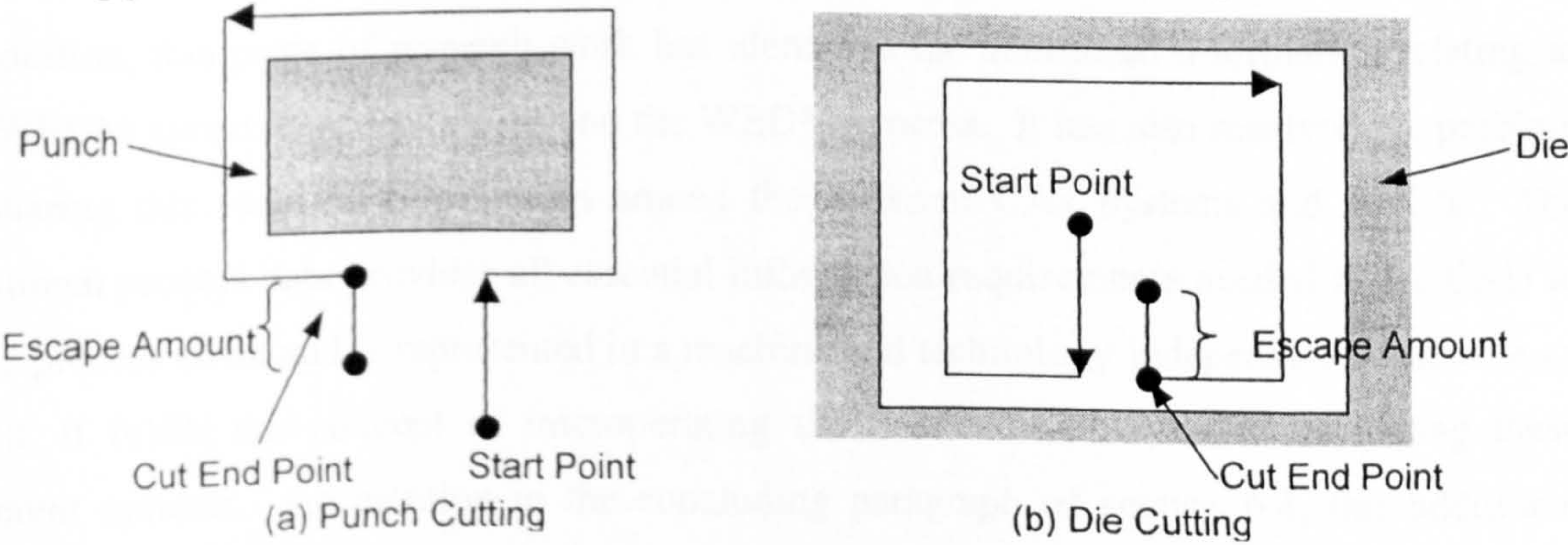


Figure 8.10 Escape amount for punch and die cutting



Nozzle gap – is the distance between the upper and low wire guides. It assists in the calculation of the tension and maximum angle of the wire, and the graphical simulation of any possible collision between the wire guides and the jigs or fixtures.

The attributes of escape amount and nozzle gap need to be added in the *wire\_edm\_machining\_operation* and *wire\_edm\_machine\_functions*, as shown in table 6.4 and table 6.2 respectively.

STEP-NC Entity	Additional Information	Wire SNIPs (ISO 14649-13)	PEPS Solid Cut (ISO 6983)	FAPT (ISO 6983)
WEDM Machining Operation	Escape amount	x	√	√
WEDM Machining Strategy	Reverse cutting	x	√	√
	No-core cutting	x	√	√
	Multiple cutting	x	√	√
	Tag identification	x	√	√
WEDM Machining Functions	Nozzle gap	x	√	√
	Automatic wire threading	x	√	√
WEDM Technology	Machining feedrate controlling	x	√	√
	Cutting parameters setting	x	√	√
Machine Information	Machining envelope	x	√	√

Table 8.4 Identification of the additional process data for the drafted ISO 14649-13

The accuracy of the output generated from the Wire SNIPs has measured up to the STEP-NC process plan featured in the case study found in the ISO/DIS 14649-13 standard. It has specified the *machining\_workingsteps* describing the task and the machining conditions under which the task has to be performed. Thus, Wire SNIPs has successfully demonstrated that the system framework for the WEDM process has identified both the essential process planning activities together with their interrelationships, and the general information requirements containing the basic data that collectively describes the applications following product design.

In addition, this piece of research work has identified the additional information relating to the WEDM manufacturing features and the WEDM process. It has also resolved the problem of sharing this essential information among the different CAx systems and CNC's. The additional process data provides all essential information requirements needed in the CAD to CNC process chain and is represented in a machine and technology independent format. As a result, it fulfils the concept of interoperating the information requirements among these different systems. As mention in the concluding paragraph of section 6.4, this additional information would make a significant contribution to the development of the ISO/DIS 14649-13 standard.



## Chapter 9

# CONCLUDING DISCUSSION

### 9.1 Introduction

This section discusses the two major research areas presented in the thesis namely the theoretical research and the experimental research. The theoretical research involved the designing of a CAX system framework and the information modelling for WEDM component manufacturing within a STEP-NC compliant manufacturing environment. As for the experimental research, it was concerned with the development and the testing of the Wire SNIPs.

### 9.2 STEP-NC compliant WEDM CAX system framework

A STEP-NC compliant CAX system framework for WEDM component manufacturing has been proposed in this thesis. It was developed with the intent of applying the evolving STEP-NC technology to support the WEDM process by modelling the process planning activities and the information requirements needed to machine the part. The system framework covered a range of WEDM process planning tasks, which included workpiece setup, machining task planning and process plan generation. The input to the system framework required the descriptions of the product design specification in the form of a PModel and the manufacturing process capability in the form of a MModel. The output from the system framework was a description of the WEDM machining operations, which was compliant with the STEP-NC standards and could be used to machine the WEDM part. It has been referred to as a STEP-NC process plan, identifying the knowledge and constraints governing the use of the process. This was in direct contrast to the NC part program based on the ISO 6983 standard. Even if ISO 6983 were to be updated with more complex toolpath types, NC codes would still be lacking in information on material types, tolerances, surface finish, expected forces, and other product or process data that could be used to support intelligent control (Procter *et al.* 2002).

The system framework played the vital role of a CAPP system linking the various product designing and manufacturing activities. Although, the CAD and CAM systems have



revolutionised NC part programming, these systems have been developed in total isolation and remained largely disintegrated. CAPP systems support the process planning by accumulating machining knowledge and reasoning capabilities, and have taken an important role in integrating CAD and CAM (Rho *et al.* 2004). Similarly, the author's system framework was designed to represent, capture, arrange and utilise the knowledge of the product design specification together with the manufacturing process capability for WEDM process planning. It made use of the IDEF0 activity modelling methodology to gain an understanding of the interactions among the various WEDM process planning activities. At higher levels of the WEDM process planning hierarchy, the choice of machines, wire tool, workpiece setup and machining operations were identified while at the lower levels, the machining conditions and machining strategies were defined together with the generation of the process plan for the given manufacturing feature of the part. As such the framework also provided an initial overview of the information flow between the activities indicating how a decision made by one activity was affected by the results of other activities.

The major goal of STEP-NC is to allow information about the product design, process planning and manufacturing execution to be exchanged among and shared by different design, engineering and manufacturing software systems. However due to the unconventional material removal characteristic of the WEDM process, it was very difficult to plan an inclusive *workplan* that worked on most WEDM machine controllers. The WEDM process was driven by a number of machining parameters and strategies, which were machine and technology dependent. For example, the offset needed to compensate for the machining gap caused by the sparking phenomenon together with the machining strategy in order to improve the accuracy of specific geometrical features, such as sharp corners, varies from machine control to machine control. The methodology for making the best choice of the machining parameters and strategies was presently assisted by the expert system based on the objective quality target criteria, including the required surface finish, workpiece and wire materials (Richard *et al.* 2004). However, the expert system was proprietary making it difficult to be standardised and causing interoperability issues between different systems. As the expert/intelligent system formed an essential part of the CAD/CAM system, the possible solution was to separate the information that the vendors were willing to exchange from the proprietary methods and procedures that they wanted to protect. The STEP-NC data model for the WEDM process aims to support such an approach by including the information that was required to execute the expert system. By doing so, the data model captured most of the



information required to produce an interoperable *workplan* that was not governed by the type of vendor systems used.

### 9.3 STEP-NC compliant WEDM information modelling

The WEDM information models aim to improve the integration between the highly automated CAD/CAPP/CAM systems and CNCs. These information models were based on the mature area of research intensely explored by several authors (Liu and Young 2004, Molina *et al.* 1995). The representation of these WEDM information models was not pursued independently but was sought in an integrated manner supporting the early evaluation of the design for manufacture. This has been carried out through the use of the STEP-NC data interface for the WEDM process, specifying the various data entities, their properties, behaviours and interactions with other entities.

Such a concept of data-driven applications, which included engineering applications and software tools, has emerged in response to the need for integrated and flexible computer environments to support design and manufacturing activities of a product (Molina and Bell 1999). As a result of integrating the WEDM information models, it supported the preliminary evaluation of both the feasibility of product design and machining process planning. The product information could be shared by machining process planning and the manufacturing information could be made available for product design.

The PModel and MModel have provided a common source of well-defined and structured information relating to the WEDM process. They provide the information requirements supporting the decision-making in the process of designing and manufacturing a product. The PModel captures all the essential data relating to the workpiece material, shape and size, the product G, D & T together with the manufacturing planning data. This data has been classified into three key elements in the PModel namely the WEDM billet, WEDM product design and WEDM manufacturing view. On the other hand, the three core elements of MModel were adapted from Molina *et al.* (1995), namely WEDM resources, WEDM processes and WEDM strategies. These elements mainly described the physical and functional properties of the WEDM process representing the resource constraints and the process capabilities respectively. They also included the representation of the various machining strategies imposed by the composition of the WEDM resources and WEDM processes through the use of the expert system, such as identifying the cutting conditions.



In addition, the extended WEDM information models have been identified to represent complete and realistic manufacturing process knowledge. It should be noted that ISO/DIS 14649-13 standard is currently in the development stage and the important machining process attributes have yet to be fully specified. These attributes were determined by making a comparison between STEP-NC and two commercial CAD/CAM systems based on the ISO 6983 standard, namely PEPS Solid Cut and FAPT. Hence, the extended information models enable the different data-driven applications to use the knowledge and support the planning of the process more effectively. However, the main challenge of WEDM information models is to facilitate a practical platform for interoperable CNC manufacturing satisfying a completely integrated manufacturing system. For example, the PEPS Solid Cut has a different perception on the machining strategies as compared to the FAPT. Therefore, the WEDM information models would have to capture the knowledge from different functional perspectives cater to most CAX needs, and thereby provide an opportunity to manufacture a part at different locations or companies.

#### 9.4 STEP-NC compliant WEDM CAX prototype system development

A computational prototype entitled Wire SNIPs has been designed and implemented to demonstrate the viability of the STEP-NC compliant information models for WEDM component manufacturing. The system exploits the instances of the PModel and MModel to generate a feasible machining *workplan* by using process planning rules in terms of the machining precedence (*workingstep*) and surface finish accuracy defined in Ra. It also provides the basis for making an important step forward in integrating the various product design and machining process planning activities and facilitating the interoperable manufacturing of the WEDM part through the use of the STEP-NC data interface. The implementation of Wire SNIPs was made up of three main stages, namely the representation of the information models, the development of the DBMS and the construction of the system application, as described in section 7.2. During the first stage, the UML was used to model the information requirements supporting the WEDM process planning activities. Although EXPRESS was used to specify the STEP-NC entities, it was inadequate for capturing functional interaction between the entities as it was more oriented towards capturing the constraints (Al-Ashabb and Young 1997). UML has clearly represented the WEDM information models in terms of classes, attributes, relationships and operations allowing the design of the database schema to be easily implemented in the object-oriented DBMS.



The ObjectStore DBMS was utilised to provide common information storage among the different data-driven applications. It was capable of extending direct information sharing to different design and manufacturing departments using the object-oriented database based on the UML. The ObjectStore DBMS was incorporated into Wire SNIPs by simply providing the vital link or interface to the Java programming language. Lastly, Wire SNIPs applications were developed in Java defining the computing operations relating to the WEDM process planning activities. The easy-to-use interface drastically reduced the amount of code required to manage the Java objects, and still provided the full capability of Java to define, manipulate and share important application data.

At the CAM level, the system was capable of generating the STEP-NC process plan for the WEDM process based on the information specified by the PModel and MModel. The information was organised in an object-oriented manner facilitating Wire SNIPs to select, to the best extent possible, the most appropriate WEDM resources, processes and strategies from the array of available options. In addition, Wire SNIPs was able to query the PModel/product database to obtain the product design specification and then query the MModel/manufacturing database for the corresponding manufacturing capabilities information. Hence, the compatibility of the product designs with the manufacturing capabilities could be determined or redesigned.

## 9.5 Testing of Wire SNIPs

Wire SNIPs has been tested to gauge the performance of its functionality. The end result generated from the system was passed onto a STEP-NC interpreter to parse it and extract data from it. In addition, the interpreter was used to activate the toolpath generator in order for the latter to calculate the toolpath for each manufacturing feature and send the wire tool motions to the machine control board, which was to produce motion/pulse signals to the motor. However, the testing of Wire SNIPs was limited to the computing functions of planning the WEDM process and generating the STEP-NC process plan. This has been primarily carried out by evaluating the product and manufacturing information based on the WEDM PModel and MModel. The product information included the geometrical, topological, tolerance, material and surface finishing quality attributes of the WEDM part. The geometrical and topological information were both represented by manufacturing feature-based representations but this was not the main focus of the thesis. As for the manufacturing information, it included information about the WEDM machining operations, wire tool and



WEDM machining parameters. This information described the required operations to machine a specific WEDM manufacturing feature, the appropriate wire tool to use, and the optimal cutting condition to perform the machining operations.

Wire SNIPs annotated the design specification of a product with richer information about the WEDM manufacturing process capabilities. All this information was reflected in the STEP-NC process plan specified in a format that was neutral to most computing platforms enabling the sharing of data among the different design and manufacturing departments. Unlike the NC part program based on the ISO 6983 standard, which merely described the cutting toolpath and the machine switching functions, the STEP-NC process plan captured the crucial information about the WEDM characteristics in the form of a *wire\_edm\_machining\_operation*. However, a certain level of detailed planning of the WEDM machining process is still required and could only be decided at the machine during runtime. The STEP-NC process plan did not specify the sequence of the events or the instant at which the unit task has to be performed, such as the turning the on/off of a switch. These decisions are instead left to the operator or in real time to the CNC (Zhang and Liu 2004). Thus, the application of the STEP-NC standards to specify the geometric and manufacturing information at the machine tool has provided the CNC with the vast opportunities to machine a part more intelligently.



## **Chapter 10**

### **CONCLUSIONS AND FUTURE WORK**

#### **10.1 Introduction**

This chapter identifies the major contribution to knowledge and the conclusions drawn from the research. It also suggested the possible further work in order to extend the application of the Wire SNIPs.

#### **10.2 Major contribution to knowledge**

The major contribution to knowledge gathered from this work include:

- The design of a STEP-NC compliant CAX system framework for WEDM component manufacturing. The framework has provided a structured methodology for the design of a WEDM CAX system exploiting the product and manufacturing information requirements defined in the newly evolved STEP-NC standard. The computational implementation of the system framework has shown to be of strong potential for industrial application. It has also demonstrated the viability of the STEP-NC standard to describe the geometrical and manufacturing requirements of a WEDM component.
- The specification of the information models supporting WEDM component manufacturing. The information models have identified the additional information to ISO/DIS 14649-13 that is essential for carrying out the WEDM operations based on industrial practices and would make a significant contribution to the development of the standard. These models have also supported the concept of interoperability within a STEP-NC compliant machining process planning environment through the exchange of product and manufacturing information across the CAX to CNC process chain.

#### **10.3 Conclusions**

The conclusions formulated from this work are as follows:

- i. The literature review on WEDM process has provided an in-depth research into the various academic works involving the improvement of the performance measures, the optimisation of the process parameters, the monitoring and control of the machining



process together with process development and applications. It has shown some possible trends for future research into the WEDM process.

- ii. The literature review on STEP-NC has highlighted the opportunity to revamp the traditional means of programming a part for CNC manufacturing. It has shown that STEP-NC facilitates the integration of the CAX systems and CNC's through its formal specification of representing and exchanging the product and manufacturing information.
- iii. A system framework has been designed to integrate the various stages of the product life cycle from product design to manufacture for the WEDM process chain. It provided a structure for the WEDM process planning activities and their relationships that were compliant with the STEP-NC standards through the use of the IDEF0 activity modelling methodology.
- iv. The system framework has also provided an overview of the information models supporting the WEDM process planning activities. These WEDM information models have effectively defined the basic system vocabulary enabling the integrated use of the information in an interoperable industrial environment by the different CAX systems and CNC's.
- v. The realisation of the WEDM information models have fully captured and represented the information relating to the design, manufacture and production functions that occurred during the design to manufacturing of a WEDM part. The application of the PModel and the MModel, which models and manages the product design and manufacturing capability for WEDM parts has provided the basis for an integrated knowledge-based process-planning environment.
- vi. The WEDM information models have formed a common base of data with which all product design and manufacturing process functions interacted, thereby providing a vital mechanism through which they were integrated. These WEDM information models have been defined through the use of the object-oriented UML, which has shown to be of significant advantage in implementing the prototype system called Wire SNIPs.



- vii. Wire SNIPs has been developed and implemented, and has shown the viability of the author's system framework. It has exploited the STEP-NC compliant WEDM information models identifying the product and manufacturing knowledge supporting the information requirements needed throughout the WEDM product life-cycle.
- viii. Wire SNIPs has shown the performance capability of WEDM process planning and the potential for the use as an industrial tool. It has been built on the basis of structuring the information models and constructing the system applications, which has provided a systemically methodology of implementing the system framework.
- ix. The testing of the Wire SNIPs has used the example test parts provided in the ISO/DIS 14649-13 standard, and thereby has proven the applicability of the research. It has evaluated not only the functionality of the system but also the information content needed to drive the system.
- x. The viability of the data residing in the STEP-NC compliant WEDM information models has been evaluated by comparing it against the programming or machining parameters needed to drive the two commercial WEDM CAD/CAM systems, namely the PEPS Solid Cut and FAPT. The comparison has shown that the WEDM extended information models provide more reliable product and manufacturing information in assisting the performance of product development life cycle activities and related decision-making processes.

#### 10.4 Future Work

The functionality of Wire SNIPs could be further explored or extended by further investigation into the following areas:

##### 10.4.1 *Consider a complete machining process logic and rules*

Due to the scope of the research reported in the thesis, the machining process logic and rules residing in Wire SNIPs have been developed for the machining of a die. However, the WEDM process is also commonly used to machine parts that required no-core cutting, multiple profile cutting and cam/cam gear cutting, as explained in section 6.4. An extension of the Wire SNIPs application therefore needs to contain more specific process logic and rules for the machining of parts that are produced by the WEDM process.



#### ***10.4.2 Include graphical display in the Wire SNIPs***

The design of the graphical user interfaces used in Wire SNIPs has concentrated only on capturing of data giving little consideration to the interpretation of the data element to the system users. In order to provide a user-friendly graphical user interface, it needs to add pictures or figures elaborating the various information requirements needed from the user. In addition, a simulation of the WEDM process based on the output generated from Wire SNIPs would also enable the user to visualise and verify the machining sequence.

#### ***10.4.3 Apply WEDM expert system to Wire SNIPs***

Wire SNIPs has simply assumed the various generator settings of the WEDM process for the example part featured in the case study. In most WEDM CAD/CAM systems, this is commonly determined through the use of the individual CNC vendor's expert system, which aims to achieve an accurate and efficient machining operation without compromising the machining performance. Further research needs to consider on implementing an expert system into the Wire SNIPs architecture in order to identify the optimal machining condition from the infinite number of combinations of the various factors affecting the WEDM process, as described in section 4.5.5.

#### ***10.4.4 Arrange output from Wire SNIPs in XML format***

The end result from Wire SNIPs was a STEP-NC process plan based on the ISO 10303-21 standard specifying an exchange structure using clear text encoding of data. The increasing use of the XML to implement e-manufacturing has generated keen research interest within the STEP-NC community. Hence, the STEP-NC process plan generated from the Wire SNIPs needs to be developed and arranged in the XML format based on the ISO/TC 10303-28 standard for the WEDM process.



## REFERENCES

600 Centre, PC FAPT cut i, 600 Centre Homepage, [www.600centre.com](http://www.600centre.com), accessed on 10th Oct 2005.

Al-Ashabb, A.H.S. and Young, R.I.M., Modelling manufacturing process information using EXPRESS, *Concurrent Eng. - Research & Applications* 5 (1) (1997) 27-35.

Albert, M., Modern Machine Shop Online, Plugging into STEP-NC, [www.mmsonline.com/articles/070203.html](http://www.mmsonline.com/articles/070203.html), accessed on 10th Oct 2005.

Alekseyev, G.A. and Korenblum, M.V., Analysis of the Conditions for the High Efficiency Wire Cut EDM, *Proceedings of the Ninth International Symposium for Electro-Machining (ISEM-9)*, Nagoya, Japan, 1989.

Ali, L., Newman, S.T. and Petzing, J., Development of a STEP-compliant inspection framework for discrete components, *Proceedings I MECH E Part B J. Eng. Manuf.* 219 (B7) (2005) 557-564.

Allen, R.D., Newman, S.T., Harding, J.A. and Rosso Jr., R.S.U., The design of a STEP-NC compliant agent based CAD/CAM system, *International Conference on Flexible Automation & Intelligent Manufacturing*, Tampa, FL, USA, 2003.

Allen, R.D., Harding, J.A. and Newman, S.T., The application of STEP-NC using agent-based process planning, *Inter. J. Prod. Research* 15 (4) (2005) 655-670.

Alting, L. and Zhang, H.C., Computer aided process planning: the state of the art survey, *Inter. J. Prod. Res.* 27 (4) (1989) 553-585.

Anand, K.N., Development of process technology in wire-cut operation for improving machining quality, *Total Quality Management* 7 (1) (1996) 11-28.

American National Standards Institute ANSI X3.37, *Programming Language APT*, 1987.

American National Standards Institute (US Product Data Association) ANSI US PRO/IPO-100-1996, *Initial Graphics Exchange Specification Version 5.3*, 1996.

American National Standards Institute ANSI Y14.26M-1981, *Initial Graphics Exchange Specification Version 1.0*, 1981.

Autodesk, Inc., Autodesk Homepage, [www.autodesk.co.uk](http://www.autodesk.co.uk), accessed on 10th Oct 2005.

Beltrami, I. and Dauw, D., A simplified post process for wire cut EDM, *J. Mater. Process. Technol.* 58 (4) (1996) 385-389.

Benavides, G.L., Bieg, L.F., Saavedra, M.P. and Bryce, E.A., High aspect ratio meso-scale parts enabled by wire micro-EDM, *Microsys. Technol.* 8 (6) (2002) 395-401.

Benedict, G.F., Electrical discharge machining (EDM), in: *Non-Traditional Manufacturing Processes*, Marcel Dekker, Inc, New York & Basel, 1987, pp. 231-232.



- Bhandarkar, M.P., Downie, B., Hardwick, M. and Nagi, R., Migrating from IGES to STEP: one to one translation of IGES drawing to STEP drafting data, *Computers In Industry* 41 (3) (2000) 261-277.
- Bloor, M.S. and Owen, J., CAD/CAM product-data exchange: the next step, *Computer-Aided Design* 23 (4) (1991) 237-243.
- Boccadoro, M. and Dauw, D.F., About the application of fuzzy controllers in high-performance die-sinking EDM machines, *Ann. CIRP* 44 (1) (1995) 147-150.
- Boothroyd, G., Winston, A.K., Non-conventional machining processes, in: *Fundamentals of machining and machine tools*, Marcel Dekker, Inc., 1989, pp. 491.
- Borja, V., Bell, R. and Harding, J.A., Assisting design for manufacture using the data model driven approach, *Proc. Instn. Mech. Engrs, Part B, J. Eng. Manuf.* 215 (B12) (2001) 1757-1771.
- Brown, D.W., Objects and classes, in: *An Introduction to Object-Oriented Analysis*, John Wiley & Sons, Inc., New York, 2002, pp. 97-147.
- Camtek Ltd, PEPS Solid Cut Wire, Camtek Homepage, [www.peps.com](http://www.peps.com), accessed on 10th Oct 2005.
- Chao, P.Y. and Wang, Y.C., A data exchange framework for networked CAD/CAM, *Computers In Industry* 44 (2) (2001) 131-140.
- Cheng, Y.M., Eubank, P.T. and Gadalla, A.M., Electrical discharge machining of ZrB<sub>2</sub>-based ceramics, *Mater. Manuf. Processes* 11 (4) (1996) 565-574.
- Cogun, C., A technique and its applications for evaluation of material removal contributions of pulses in electrical discharge machining, *Inter. J. Mach. Tools Manuf.* 30 (1) (1990) 19-31.
- Colquhoun, G.J., Baines, R.W. and Crossley, R., A state of the art review of IDEF0, *Inter. J. Computer Integrated Manuf.* 6 (4) (1993) 252-264.
- Dauw, D.F., Sthioul, H. and Tricarico, C., Wire analysis and control for precision EDM cutting, *Ann. CIRP* 38 (1) (1989) 191-194.
- Dauw, D.F., Brown, C.A., Van Griethuysen, J.P. and Albert, J.F.L.M., Surface topography investigations by fractal analysis of spark-eroded, electrically conductive ceramics, *Ann. CIRP* 39 (1) (1990) 161-165.
- Dauw, D.F. and Albert, L., About the evolution of wire tool performance in wire EDM, *Ann. CIRP* 41 (1) (1992) 221-225.
- Dauw, D.F. and Beltrami, I., High-precision wire-EDM by online wire positioning control, *Ann. CIRP* 43 (1) (1994) 193-197.
- De Bruyn, H.E. and Pekelharing, A.J., Has the delay time influence on the EDM-process?, *Ann. CIRP* 31 (1) (1982) 103-106.



- Dekeyser, W., Snoeys, R. and Jennes, M., A thermal model to investigate the wire rupture phenomenon for improving performance in EDM wire cutting, *J. Manuf. Syst.* 4 (2) (1985) 179-190.
- Dekeyser, W., Snoeys, R. and Jennes, M., Expert system for wire cutting EDM based on pulse classification and thermal modelling, *Robotics Comput. Integrated Manuf.* 4 (1-2) (1988) 219-224.
- Dekeyser, W.L. and Snoeys, R., Geometric Accuracy of Wire EDM, *Proceedings of the Ninth International Symposium for Electro-Machining (ISM-9)*, Nagoya, Japan, 1989.
- DeVries, M.F., Duffie, N.A., Kruth, J.P., Dauw, D.F. and Schumacher, B., Integration of EDM within a CIM environment, *Ann. CIRP* 39 (2) (1990) 665-672.
- German National Standard DIN 66301, Verband Der Automobilindustrie Flachen Schnittstelle (VDA-FS), 1986.
- Dutta, D., Kumar, V., Pratt, M.J. and Sriram, R.D., Towards STEP-based data transfer in layered manufacturing, *Proceedings of the 10th IFIP WG5.2/5.3 PROLAMAT Conference*, Trento, Italy, 1998.
- Eastman, C., Out of STEP, *Computer-Aided Design* 26 (5) (1994) 338-340.
- Egashira, K. and Mizutani, K., Ultrasonic vibration drilling of microholes in glass, *Ann. CIRP* 51 (1) (2002) 339-342.
- El-Midany, T.T., El-Keran, A.A. and Radwan, H.T., CAM system for efficient generation of part-programs for wire-edm, *7th Cairo University International MDP Conference*, Cairo, Egypt, 2000.
- Enache, S. and Opran, C., Dynamic stability of the technological machining system in EDM, *Ann. CIRP* 42 (1) (1993) 209-214.
- Feeney, A.B., Kramer, T., Proctor, F., Hardwick, M. and Loffredo, D., STEP-NC implementation - ARM or AIM?, *ISO T24 STEP-Manufacturing Meeting*, San Diego, CA, 2003.
- Firestone, R.F., *Ceramic-Applications in Manufacturing*, Society of Manufacturing Engineers, Michigan, 1988, pp. 133.
- Gadalla, A.M. and Tsai, W., Machining of WC-Co composites, *Mater. Manuf. Processes* 4 (3) (1989) 411-423.
- Gao, J.X. and Huang, X.X., Product and manufacturing capability modelling in an integrated CAD/process planning environment, *Inter. J. Adv. Manuf. Technol.* 11 (1) (1996) 43-51.
- Garbajs, V., Statistical model for an adaptive control of EDM-process, *Ann. CIRP* 34 (1) (1985) 499-502.



- Giachetti, R.E., A standard manufacturing information model to support design for manufacturing in virtual enterprise, *Proc. Instn. Mech. Engrs, Part B, J. Eng. Manuf.* 213 (B3) (1999) 225-246.
- Gökler, M.I. and Ozanözü, A.M., Experimental investigation of effects of cutting parameters on surface roughness in the WEDM process, *Inter. J. Mach. Tools Manuf.* 40 (13) (2000) 1831-1848.
- Goldstein, B.L.M., Kemmerer, S.J. and Parks, C.H., A brief history of early product data exchange standards - NISTIR 6221, National Institute of Standards and Technology, 1998.
- Gu, P., Zhang, Y. and Norrie, D.H., Object-orient product modelling for computer-integrated manufacturing, *Inter. J. Computer Integrated Manuf.* 7 (1) (1994) 17-28.
- Guo, Z.N., Lee, T.C., Yue, T.M. and Lau, W.S., A study of ultrasonic-aided wire electrical discharge machining, *J. Mater. Process. Technol.* 63 (1-3) (1997) 823-828.
- Guo, Z.N., Wang, X., Huang, Z.G. and Yue, T.M., Experimental investigation into shaping particle-reinforced material by WEDM-HS, *J. Mater. Process. Technol.* 129 (1-3) (2002) 56-59.
- Ham, I. and Lu, S.C.Y., Computer-aided process planning: the present and the future, *Ann. CIRP* 37 (2) (1988) 591-601.
- Han, F., Kunieda, M., Sendai, T. and Imai, Y., High precision simulation of WEDM using parametric programming, *Ann. CIRP* 51 (1) (2002) 165-168.
- Hardwick, M., What you should know about STEP, *Machine Design*, Penton Media, Cleveland, OH, 72 (13) (2000) 98-102.
- Hardwick, M., e-Manufacturing using STEP-NC, EMO STEP-NC Seminar, Hanover, Germany, 2001.
- Hardwick, M. and Loffredo, D., STEP into NC, *Manuf. Eng.*, Society of Manuf. Engineers, Dearborn, Michigan, 126 (1) (2001) 38-50.
- Ho, K.H. and Newman, S.T., State of the art electrical discharge machining (EDM), *Inter. J. Mach. Tools Manuf.* 43 (13) (2003) 1287-1300.
- Ho, K.H., Newman, S.T., Rahimifard, S. and Allen, R.D., State of the art in wire electrical discharge machining (WEDM), *Inter. J. Mach. Tools Manuf.* 44 (12-13) (2004) 1247-1259.
- Ho, K.H., Newman, S.T. and Allen, R.D., The design of a STEP-NC compliant wire EDM CAD/CAPP/CAM system, *International Conference on Flexible Automation & Intelligent Manufacturing*, Bilbao, Spain, 2005.
- Hsue, W.J., Liao, Y.S. and Lu, S.S., Fundamental geometry analysis of wire electrical discharge machining in corner cutting, *Inter. J. Mach. Tools Manuf.* 39 (4) (1999) 651-667.



- Huang, Y.H., Zhao, G.G., Zhang, Z.R. and Yu, C.Y., The identification and its means of servo feed adaptive control system in WEDM, *Ann. CIRP* 35 (1) (1986) 121-123.
- Huang, J.T. and Liao, Y.S., A Study of Finish Cutting Operation Number & Machining Parameters Setting in Wire Electrical Discharge Machining, *Proceedings of International Conference on Precision Machining (ICPE'97)*, Taipei, Taiwan, 1997.
- Huang, J.T., Liao, Y.S. and Hsue, W.J., Determination of finish-cutting operation number and machining-parameters setting in wire electrical discharge machining, *J. Mater. Process. Technol.* 87 (1-3) (1999) 69-81.
- Huang, J.T. and Liao, Y.S., A wire-EDM maintenance and fault-diagnosis expert system integrated with an artificial neural network, *Inter. J. Prod. Res.* 38 (5) (2000) 1071-1082.
- Huang, J.T. and Liao, Y.S., Optimization of machining parameters of wire-EDM based on grey relational and statistical analyses, *Inter. J. Prod. Res.* 41 (8) (2003) 1707-1720.
- Huntress, E.A., Electrical discharge machining, *American Machinist*, 122 (8) (1978) 83-98.
- ICAM Technologies Corporation, ICAM Homepage, [www.icam.com](http://www.icam.com), accessed on 10th Oct 2005.
- International Organisation for Standardisation ISO/IEC 646, Information technology - ISO 7-bit coded character set for information interchange, 1991.
- ISO International Standard 6983 Part 1, Numerical control of machines - Program format and definition of address words - Part 1: Data format for positioning, line motion and contouring control systems, 1982.
- ISO International Standard 10303 Part 1, Industrial automation systems and integration - Product data representation and exchange - Part 1: Overview and fundamental principles, 1994.
- ISO International Standard 10303 Part 11, Industrial automation systems and integration - Product data representation and exchange - Part 11: Description Methods: The EXPRESS language reference manual, 2004.
- ISO International Standard 10303 Part 21, Industrial automation systems and integration - Product data representation and exchange - Part 21: Implementation methods: Clear text encoding of the exchange structure, 2002.
- ISO International Standard 10303 Part 22, Industrial automation systems and integration - Product data representation and exchange - Part 22: Implementation methods: Standard data access interface, 1998.
- ISO International Standard 10303 Part 31, Industrial automation systems and integration - Product data representation and exchange - Part 31: Conformance testing methodology and framework: General concepts, 1994.



ISO International Standard 10303 Part 41, Industrial automation systems and integration - Product data representation and exchange - Part 41: Integrated generic resource: Fundamentals of product description and support, 2000.

ISO International Standard 10303 Part 42, Industrial automation systems and integration - Product data representation and exchange - Part 42: Integrated generic resource: Geometric and topological representation, 2003.

ISO International Standard 10303 Part 101, Industrial automation systems and integration - Product data representation and exchange - Part 101: Integrated application resources: Draughting, 1994.

ISO International Standard 10303 Part 104, Industrial automation systems and integration - Product data representation and exchange - Part 104: Integrated application resource: Finite element analysis, 2000.

ISO International Standard 10303 Part 203, Industrial automation systems and integration - Product data representation and exchange - Part 203: Application protocol: Configuration controlled 3D designs of mechanical parts and assemblies, 1994.

ISO International Standard 10303 Part 214, Industrial automation systems and integration - Product data representation and exchange - Part 214: Application protocol: Core data for automotive mechanical design processes, 2003.

ISO International Standard 10303 Part 240, Industrial automation systems and integration - Product data representation and exchange - Part 240: Application protocol: Process plans for machined products, 2003.

ISO International Standard 10303 Part 514, Industrial automation systems and integration - Product data representation and exchange - Part 514: Application interpreted construct: Advanced boundary representation, 1999.

ISO International Standard 14649 Part 1, Industrial automation systems and integration - Physical device control - Data model for computerised numerical controllers - Part 1: Overview and fundamental principles, 2003.

ISO International Standard 14649 Part 10, Industrial automation systems and integration - Physical device control - Data model for computerised numerical controllers - Part 10: General process data, 2004.

ISO International Standard 14649 Part 11, Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 11: Process data for milling, 2004.

ISO International Standard/Comittee Draft 10303 Part 219, Industrial automation system - Product data representation and exchange - Part 219: Dimensional inspection information exchange, 2002.



ISO International Standard/Committee Draft 14649 Part 14, Industrial automation systems and integration - Physical device control - Data model for computerised numerical controllers - Part 14: Process data for sink-edm, 2002.

ISO International Standard/Draft International Standard 10303 Part 224, Industrial automation systems and integration - Product data representation and exchange - Part 224: Application protocol: Mechanical product definition for process planning using machining features, 2000.

ISO International Standard/Draft International Standard 10303 Part 238, Industrial automation systems and integration - Product data representation and exchange - Part 238: Application Protocol: Application interpreted model for computerized numeric controllers, 2004.

ISO International Standard/Draft International Standard 14649 Part 13, Industrial automation systems and integration - Physical device control - Data model for computerised numerical controllers - Part 13/1: Process data for wire-edm, 2003.

ISO International Standard/Proof of a new International Standard 14649 Part 12, Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 12: Process data for turning, 2004.

ISO International Standard/Technical Specification 10303 Part 27, Industrial automation systems and integration - Product data representation and exchange - Part 27: Implementation methods: Java TM programming language binding to the standard data access interface with Internet/Intranet extensions, 2000.

ISO International Standard/Technical Specification 10303 Part 28, Industrial automation systems and integration - Product data representation and exchange - Part 28: Implementation methods: XML representations of EXPRESS schemas and data, 2003.

ISO International Standard/Technical Specification 10303 Part 304, Industrial automation systems and integration - Product data representation and exchange - Part 304: Abstract test suite: Mechanical design using boundary representation, 2001.

Jameson, E.C., Description and development of electrical discharge machining (EDM), in: Electrical Discharge Machining, Society of Manufacturing Engineers, Dearborn, Michigan, 2001, pp. 16.

Jennes, M., Dekeyser, W. and Snoeys, R., Comparison of various approaches to model the thermal load on the EDM-wire electrode, Ann. CIRP 33 (1) (1984) 93-98.

Jennes, M. and Snoey, R., Correlation between EDM data and machining settings, Ann. CIRP 24 (2) (1984) 83-88.

Jones, P.F., Numerical control program generation, in: CAD/CAM Features, Applications & Management, The Macmillian Press Ltd, Hong Kong, 1992, pp. 158.

Kalpajian, S. and Schmid, S.R., Material Removal Processes: Abrasive, Chemical, Electrical & High-Energy Beam, in: Manufacturing Processes for Engineering Materials, Prentice Hall, New Jersey, 2003, pp. 544.



- Kemmerer, S.J., STEP: the grand experience (Editor of) NIST Special Publication 939, National Institute of Standards and Technology, Gaithersburg, MD, 1999.
- Kinoshita, N., Fukui, M., Shichida, H., Gamo, G. and Sata, T., Study on E.D.M. with wire electrode; gap phenomena, *Ann. CIRP* 25 (1) (1976) 141-145.
- Kinoshita, N., Fukui, M. and Gamo, G., Control of wire-EDM preventing electrode from breaking, *Ann. CIRP* 31 (1) (1982) 111-114.
- Kinoshita, N., Fukui, M. and Kimura, Y., Study on Wire-EDM: in process measurement of mechanical behaviour of electrode-wire, *Ann. CIRP* 33 (1) (1984) 89-92.
- Kiritsis, D., Prototype STEP-NC in wire-EDM manufacturing, EMO STEP-NC Seminar, Hanover, Germany, 2001.
- Konda, R., Rajurkar, K.P., Bishu, R.R., Guha, A. and Parson, M., Design of experiments to study and optimize process performance, *Inter. J. Qual. Reliab. Manage.* 16 (1) (1999) 56-71.
- Konig, W., Dauw, D.F., Levy, G. and Panten, U., EDM - future steps towards the machining of ceramics, *Ann. CIRP* 37 (2) (1988) 623-631.
- Krar, S.F., Check, A.F., Electrical Discharge Machining, in: *Technology of Machine Tools*, Glencoe/McGraw-Hill, New York, 1997, pp. 800.
- Kruth, J.P., Snoey, R., Lauwers, B. and Juwet, M., A generalised post-processor and process-planner for five-axes wire edm machines, *Ann. CIRP* 37 (1) (1988) 203-208.
- Kruusing, A., Leppavuori, S., Uusimaki, A., Petretis, B. and Makarova, O., Micromachining of magnetic materials, *Sensors & Actuators* 74 (1-3) (1999) 45-51.
- Kunieda, M., Kojima, H. and Kinoshita, N., On-line detection of EDM spark locations by multiple connection of branched electric wires, *Ann. CIRP* 39 (1) (1990) 171-174.
- Kunieda, M. and Furudate, C., High precision finish cutting by dry WEDM, *Ann. CIRP* 50 (1) (2001) 121-124.
- Langen, H.H., Masuzawa, T. and Fujino, M., Modular method for microparts machining and assembly with self-alignment, *Ann. CIRP* 44 (1) (1995) 173-176.
- Lau, W.S. and Lee, W.B., A comparison between EDM wire-cut and laser cutting of carbon fibre composite materials, *Mater. Manuf. Processes* 6 (2) (1991) 331-342.
- Lau, W.S., Yue, T.M., Lee, T.C. and Lee, W.B., Un-conventional machining of composite materials, *J. Mater. Process. Technol.* 48 (1-4) (1995) 199-205.
- Lee, W. and Bang, Y.B., Design and implementation of an ISO14649 compliant CNC milling machine, *Inter. J. Production Research* 41 (13) (2003) 3007-3017.
- Levy, G.N. and Wertheim, R., EDM-machining of sintered carbide compacting dies, *Ann. CIRP* 37 (1) (1988) 175-178.



- Levy, G.N. and Maggi, F., WED machinability comparison of different steel grades, *Ann. CIRP* 39 (1) (1990) 183-185.
- Levy, G.N., Environmentally friendly and high-capacity dielectric regeneration for wire EDM, *Ann. CIRP* 42 (1) (1993) 227-230.
- Lewis, J., One STEP closer, *Design News*, Reed Elsevier, London, UK, 57 (20) (2002) 44-46.
- Liao, Y.S., Chu, Y.Y. and Yan, M.T., Study of wire breaking process and monitoring of WEDM, *Inter. J. Mach. Tools Manuf.* 37 (4) (1997) 555-567.
- Liao, Y.S., Huang, J.T. and Su, H.C., A study on the machining parameters optimization of wire electrical discharge machining, *J. Mater. Process. Technol.* 71 (3) (1997) 487-493.
- Liao, Y.S. and Woo, J.C., The effects of machining settings on the behavior of pulse trains in the WEDM process, *J. Mater. Process. Technol.* 71 (3) (1997) 433-439.
- Liao, Y.S. and Woo, J.C., A New Fuzzy Control System for the Adaptive Control of WEDM Process, *Proceedings of the Twelfth International Symposium for Electro-Machining (ISEM-12)*, Aachen, Germany, 1998.
- Liao, Y.S. and Woo, J.C., Design of a fuzzy controller for the adaptive control of WEDM process, *Inter. J. Mach. Tools Manuf.* 40 (15) (2000) 2293-2307.
- Lim, S.H., Juster, N. and Pennington, A.D., An information support system for enterprise integration, *Concurrent Eng.: Research & Applications* 5 (1) (1997) 13-25.
- Lin, C.T., Chung, I.F. and Huang, S.Y., Improvement of machining accuracy by fuzzy logic at corner parts for wire-EDM, *Fuzzy Sets Syst.* 122 (3) (2001) 499-511.
- Liu, C.L. and Esterling, D., Solid modeling of 4-axis wire EDM cut geometry, *Computer-Aided Design* 29 (12) (1997) 803-810.
- Liu, S. and Young, R.I.M., Utilizing information and knowledge models to support global manufacturing co-ordination decisions, *Inter. J. Computer Integrated Manuf.* 17 (6) (2004) 479-492.
- Lok, Y.K. and Lee, T.C., Processing of advanced ceramics using the wire-cut EDM process, *J. Mater. Process. Technol.* 63 (1-3) (1997) 839-843.
- Luo, Y.F., Chen, C.G. and Tong, Z.F., Investigation of silicon wafering by wire EDM, *J. Mater. Sci.* 27 (21) (1992) 5805-5810.
- Luo, Y.F., An energy-distribution strategy in fast-cutting wire EDM, *J. Mater. Process. Technol.* 55 (3-4) (1995) 380-390.
- Luo, Y.F., Rupture failure and mechanical strength of the electrode wire used in wire EDM, *J. Mater. Process. Technol.* 94 (2-3) (1999) 208-215.



- Masuzawa, T., Fujino, M., Kobayashi, K., Suzuki, T. and Kinoshita, N., Wire electro-discharge grinding for micro-machining, *Ann. CIRP* 34 (1) (1985) 431-434.
- Masuzawa, T., Tsukamoto, J. and Fujino, M., Drilling of deep microholes by EDM, *Ann. CIRP* 38 (1) (1989) 195-198.
- Masuzawa, T., Kuo, C.L. and Fujino, M., A combined electrical machining process for micronozzle fabrication, *Ann. CIRP* 43 (1) (1994) 189-192.
- Masuzawa, T. and Tonshoff, H.K., Three-dimensional micromachining by machine tools, *Ann. CIRP* 46 (2) (1997) 621-628.
- Matsuo, T. and Oshima, E., Investigation on the optimum carbide content and machining condition for wire EDM of zirconia ceramics, *Ann. CIRP* 41 (1) (1992) 231-234.
- McGeough, J.A., Electrodischarge Machining, in: *Advanced Methods of Machining*, Chapman & Hall, London, 1988, pp. 130.
- McKay, A., Bloor, M.S. and Owen, J., Application protocols: a position paper, *Proceedings of European Product Data Technology Days, Revue internationale de CFAO*, Paris, France, 1994.
- McMahon, C.A., Cox, D.R., Sims Williams, J.H. and Scott, J.A., Representation and reasoning in computer aided process planning, *Proc. Instn. Mech. Engrs, Part B, J. Eng. Manuf.* 211 (B6) (1997) 473-485.
- McMahon, C. and Browne, J., *CADCAM Principles, Practice & Manufacturing Management*, Addison Wesley Longman Limited, England, 1998.
- Ming, X.G., Mak, K.L. and Yan, J.Q., A PDES/STEP-based information model for computer-aided process planning, *Robotics & Computer-Integrated Manuf.* 14 (5-6) (1998) 347-361.
- Mohri, N., Fukuzawa, Y., Tani, T., Saito, N. and Furutani, K., Assisting electrode method for machining insulating ceramics, *Ann. CIRP* 45 (1) (1996) 201-204.
- Mohri, N., Yamada, H., Furutani, K., Narikiyo, T. and Magara, T., System identification of wire electrical discharge machining, *Ann. CIRP* 47 (1) (1998) 173-176.
- Mohri, N., Fukuzawa, Y., Tani, T. and Sata, T., Some considerations to machining characteristics of insulating ceramics-towards practical use in industry, *Ann. CIRP* 51 (1) (2002) 161-164.
- Molina, A., Ellis, T.I.A., Young, R.I.M. and Bell, R., Modelling manufacturing capability to support concurrent engineering, *Concurrent Eng.: Research & Applications* 3 (1) (1995) 29-42.
- Molina, A. and Bell, R., A manufacturing model representation of a flexible manufacturing facility, *Proc. Instn. Mech. Engrs, Part B, J. Eng. Manuf.* 213 (B3) (1999) 225-246.
- National Institute of Standards and Techonolgy, STEP on a Page, [www.nist.gov/sc5/soap/](http://www.nist.gov/sc5/soap/), accessed on 10th Oct 2005.



- Newman, S.T., Integrated CAD/CAPP/CAM/CNC manufacture for the 21st Century, International Conference in Flexible Automation & Intelligent Manufacture, Toronto, Canada, 2004.
- Nguyen, V.K. and Stroud, I., STEP-NC for EDM in Switzerland, STEP-NC Seminar, WZL RWTH Aachen, Germany, 2003.
- Obara, H., Iwata, Y. and Ohsumi, T., An Attempt to Detect Wire Temperature Distribution During Wire EDM, Proceedings of the Eleventh International Symposium for Electro-Machining (ISEM-11), Lausanne, Switzerland, 1995.
- ObjectStore, Java Interface to ObjectStore Tutorial, ObjectStore Release 6.1 Service Pack 1, 2003.
- Owen, J., STEP: an introduction, Information Geometers, Winchester, UK, 1993.
- Ozturk, N. and Ozturk, F., Neural network based non-standard feature recognition to integrate CAD and CAM, Computers in Industry 45 (2) (2001) 123-135.
- Pandit, S.M. and Wittig, W.H., A data-dependent systems approach to optimal microcomputer control illustrated by EDM, J. Eng. Ind. (Trans. ASME) 106 (2) (1984) 137-142.
- Potter, C.D., CAD workers of the world - unite, Computer Graphics World, 23 (8) (2000) 42-48.
- Procter, F.M., Michaloski, J.L. and Shackleford, W.P., Tying together design, process planning and machining with STEP-NC technology, World Automation Congress (WAC) as part of the International Symposium on Manufacturing and Applications (ISOMA), Orlando, Florida, 2002.
- Progress Software Corporation, ObjectStore DBMS, Progress Software Homepage, [www.progress.com](http://www.progress.com), accessed on 10th Oct 2005.
- Puri, A.B. and Bhattacharyya, B., An analysis and optimisation of the geometrical inaccuracy due to wire lag phenomenon in WEDM, Inter. J. Mach. Tools Manuf. 43 (2) (2003) 151-159.
- Qu, J., Shih, A.J. and Scattergood, R.O., Development of the cylindrical wire electrical discharge machining process, part 1: concept, design, and material removal rate, J. Manuf. Sci. Eng. 124 (3) (2002) 702-707.
- Qu, J., Shih, A.J. and Scattergood, R.O., Development of the cylindrical wire electrical discharge machining process, part 2: surface integrity and roundness, J. Manuf. Sci. Eng. 124 (3) (2002) 708-714.
- Quantrani, T., Visual modelling with rational rose 2000 and UML, Addison-Wesley, 2000.
- Rajurkar, K.P. and Wang, W.M., Real-time stochastic model and control of EDM, Ann. CIRP 39 (1) (1990) 187-190.
- Rajurkar, K.P., Wang, W.M. and Lindsay, R.P., On-line monitor and control for wire breakage in WEDM, Ann. CIRP 40 (1) (1991) 219-222.



- Rajurkar, K.P. and Wang, W.M., Thermal modelling and on-line monitoring of wire-EDM, *J. Mater. Process. Technol.* 38 (1-2) (1993) 417-430.
- Rajurkar, K.P., Wang, W.M. and McGeough, J.A., WEDM identification and adaptive control for variable-height components, *Ann. CIRP* 43 (1) (1994) 199-202.
- Rajurkar, K.P. and Wang, W.M., Improvement of EDM performance with advanced monitoring and control systems, *J. Manuf. Sci. Eng.* 119 (1997) 770-775.
- Rajurkar, K.P., Wang, W.M. and Zhao, W.S., WEDM-adaptive control with a multiple input model for identification of workpiece height, *Ann. CIRP* 46 (1) (1997) 147-150.
- Reed, K., Harrod, D.J. and Conroy, W., Initial Graphics Exchange Specification Version 5.0 NISTIR 4412, National Institute of Standards and Technology, Gaithersburg, USA, 1990.
- Rho, H.M., Park, M.W., Ha, S., Kim, J.K., Park, S., Kim, Y.S. and Lim, J.S., Computer-aided machining process planning systems: current status and future directions from a Korean perspective, *Intelligent Manufacturing System International Forum, Villa Erba - Cernobbio, Italy, 2004.*
- Rhoney, B.K., Shih, A.J., Scattergood, R.O., Akemon, J.L., Gust, D.J. and Grant, M.B., Wire electrical discharge machining of metal bond diamond wheels for ceramic grinding, *Inter. J. Mach. Tools Manuf.* 42 (12) (2002) 1355-1362.
- Rhoney, B.K., Shih, A.J., Scattergood, R.O., Ott, R. and McSpadden, S.B., Wear mechanism of metal bond diamond wheels trued by wire electrical discharge machining, *Wear* 252 (7-8) (2002) 644-653.
- Richard, J., Nguyen, V.K. and Stroud, I., Standardisation of the manufacturing process: IMS/EU STEP-NC project on the Wire EDM process, *Intelligent Manufacturing System International Forum, Villa Erba - Cernobbio, Italy, 2004.*
- Rosso Jr, R.S.U., Newman, S.T. and Rahimifard, S., The adoption of STEP-NC for the manufacture of asymmetric rotational components, *Proceedings I MECH E Part B J. Eng. Manuf.* 218 (11) (2004) 1639-1644.
- Rowell, A., The challenge of CAD interoperability, *Computer Graphics World*, 20 (6) (1997) 57-72.
- Rozenek, M., Kozak, J., Dabrowski, L. and Lubkowski, K., Electrical discharge machining characteristics of metal matrix composites, *J. Mater. Process. Technol.* 109 (3) (2001) 367-370.
- RS 274D Electronic Industries Association, Interchangeable variable block data format for positioning, contouring, and contouring/positioning numerically controlled machines, 1979.
- Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F. and Lorensen, W., Object modelling, in: *Object-Oriented Modeling & Design*, Prentice Hall, New Jersey, 1991, pp. 21-56.



- Sanchez, J.A., Cabanes, I., Lopez de Lacalle, L.N. and Lamikiz, A., Development of optimum electrodischarge machining technology for advanced ceramics, *Inter. J. Adv. Manuf. Technol.* 18 (12) (2001) 897-905.
- Scott, D., Boyina, S. and Rajurkar, K.P., Analysis and optimization of parameter combination in wire electrical discharge machining, *Inter. J. Prod. Res.* 29 (11) (1991) 2189-2207.
- Shah, J.J. and Rogers, M.T., Functional requirements and conceptual design of the feature-based modelling system, *Computer-Aided Engineering Journal* 5 (1) (1988) 9-15.
- Shobert, E.I., What happens in EDM, in: Jameson, E.C. (Ed.), *Electrical Discharge Machining: Tooling, Methods & Applications*, Society of Manufacturing Engineers, Dearborn, Michigan, 1983, pp. 3-4.
- Shoda, K., Kaneko, Y., Nishimura, H., Kunieda, M. and Fan, M.X., Adaptive Control of WEDM with On-line Detection of Spark Locations, *Proceedings of the Tenth International Symposium for Electro-Machining (ISEM-10)*, Magdeburg, Germany, 1992.
- Smith, G.L., Utilisation of STEP AP210 at the Boeing Company, *Computer-Aided Design* 34 (14) (2002) 1055-1062.
- Snoeys, R., Dauw, D.F. and Kruth, J.P., Survey of EDM adaptive control in electro discharge machining, *J. Manuf. Syst.* 2 (2) (1983) 147-164.
- Snoeys, R., Staelens, F. and Dekeyser, W., Current trends in non-conventional material removal processes, *Ann. CIRP* 35 (2) (1986) 467-480.
- Snoeys, R., Dekeyser, W. and Tricarico, C., Knowledge-based system for wire EDM, *Ann. CIRP* 37 (1) (1988) 197-202.
- Sormaz, D.N. and Khoshnevis, B., Process planning knowledge representation using an object-oriented data model, *Inter. J. Computer Integrated Manuf.* 10 (1-4) (1997) 92-104.
- Spedding, T.A. and Wang, Z.Q., Parametric optimization and surface characterization of wire electrical discharge machining process, *Precision Eng.* 20 (1) (1997) 5-15.
- Spedding, T.A. and Wang, Z.Q., Study on modeling of wire EDM process, *J. Mater. Process. Technol.* 69 (1-3) (1997) 18-28.
- Spur, G. and Schönbeck, J., Anode erosion in wire-EDM-a theoretical model, *Ann. CIRP* 42 (1) (1993) 253-256.
- STEP Tools Inc., STEP Tools Homepage, [www.steptools.com](http://www.steptools.com), accessed on 10th Oct 2005.
- Stovicek, D.R., *The state-of-the-art EDM Science, Tooling and Production*, Nelson Publishing Inc., Ohio, US, 59 (2) (1993) 42.
- Suh, S.H., Cho, J.H. and Hong, H.D., On the architecture of intelligent STEP-compliant CNC, *Inter. J. Computer Integrated Manuf.* 15 (2) (2002) 168-177.



- Suh, S.H., Lee, B.E., Chung, D.H. and Cheon, S.U., Architecture and implementation of a shop-floor programming system for STEP-compliant CNC, *Computer-Aided Design* 35 (12) (2003) 1069-1083.
- Sun, X.Q., Masuzawa, T. and Fujino, M., Micro ultrasonic machining and its applications in MEMS, *Sensors & Actuators A* 57 (2) (1996) 159-164.
- Sun Microsystems, Inc., Sun Developer Network, <http://java.sun.com>, accessed on 20th August 2005.
- Suzuki, Y. and Kishi, M., Improvement of Surface Roughness in Wire EDM, *Proceedings of the Ninth International Symposium for Electro-Machining (ISEM-9)*, Nagoya, Japan, 1989.
- Tanimura, T., Heuvelman, C.J. and Vennstra, P.C., The properties of the servo gap sensor with wire spark-erosion machining, *Ann. CIRP* 26 (1) (1977) 59-63.
- Tarng, Y.S., Ma, S.C. and Chung, L.K., Determination of optimal cutting parameters in wire electrical discharge machining, *Inter. J. Mach. Tools Manuf.* 35 (12) (1995) 1693-1701.
- Thilmany, J., *Speaking different languages*, Mech. Eng., ASME International, New York, US, 123 (2) (2001) 53-55.
- Toh, K.T.K., Newman, S.T. and Bell, R., An information systems architecture for small metalworking companies, *Proc. Instn. Mech. Engrs, Part B, J. Eng. Manuf.* 212 (B2) (1998) 87-103.
- Tosun, N., Cogun, C. and Inan, A., The effect of cutting parameters on workpiece surface roughness in wire EDM, *Machining Sci. Technol.* 7 (2) (2003) 209-219.
- Tsai, H.C., Yan, B.H. and Huang, F.Y., EDM performance of Cr/Cu-based composite electrodes, *Inter. J. Mach. Tools Manuf.* 43 (3) (2003) 245-252.
- UGS Corp., UGS Homepage, [www.ugsplm.co.uk](http://www.ugsplm.co.uk), accessed on 10th Oct 2005.
- Wang, J. and Ravani, B., Computer aided contouring operation for travelling wire electric discharge machining (EDM), *Computer-Aided Design* 35 (10) (2003) 925-934.
- Watanabe, H., Sato, T., Suzuki, I. and Kinoshita, N., WEDM monitoring with a statistical pulse-classification method, *Ann. CIRP* 39 (1) (1990) 175-178.
- Waurzyniak, P., *Moving toward the e-factory*, Manuf. Eng., Society of Manuf. Engineers, Dearborn, Michigan, 127 (5) (2001) 42-60.
- Weck, M. and Wolf, J., *Introduction to STEP-NC*, STEP-NC Seminar, WZL RWTH Aachen, Germany, 2003.
- Weston, R.H., Integration infrastructure requirements for agile manufacturing systems, *Proc. Instn. Mech. Engrs, Part B, J. Eng. Manuf.* 212 (6) (1998) 423-437.



- Williams, R.E. and Rajurkar, K.P., Study of wire electrical discharge machined surface characteristics, *J. Mater. Process. Technol.* 28 (1-2) (1991) 127-138.
- Xu, X.W. and He, Q., Striving for a total integration of CAD, CAPP, CAM and CNC, *Robotics & Computer-Integrated Manuf.* 20 (2) (2004) 101-109.
- Yan, M.T. and Liao, Y.S., Adaptive Control of WEDM Process Using the Fuzzy Control Strategy, *Proceedings of the Eleventh International Symposium for Electro-Machining (ISEM-11)*, Lausanne, Switzerland, 1995.
- Yan, M.T. and Liao, Y.S., Monitoring and self-learning fuzzy control for wire rupture prevention in wire electrical discharge machining, *Inter. J. Mach. Tools Manuf.* 36 (3) (1996) 339-353.
- Yan, M.T. and Liao, Y.S., A self-learning fuzzy controller for wire rupture prevention in WEDM, *Inter. J. Adv. Manuf. Technol.* 11 (4) (1996) 267-275.
- Yan, M.T. and Liao, Y.S., Adaptive control of the WEDM process using the fuzzy control strategy, *J. Manuf. Syst.* 17 (4) (1998) 263-274.
- Yan, M.T., Li, H.P. and Liang, J.F., The application of fuzzy control strategy in servo feed control of wire electrical discharge machining, *Inter. J. Adv. Manuf. Technol.* 15 (11) (1999) 780-784.
- Yan, B.H., Wang, C.C., Liu, W.D. and Huang, F.Y., Machining characteristics of  $Al_2O_3/6061Al$  composite using rotary EDM with a dislike electrode, *Inter. J. Adv. Manuf. Technol.* 16 (5) (2000) 322-333.
- Yan, M.T., Liao, Y.S. and Chang, C.C., On-line estimation of workpiece height by using neural networks and hierarchical adaptive control of WEDM, *Inter. J. Adv. Manuf. Technol.* 18 (12) (2001) 884-891.
- Yang, M.Y. and Park, J.H., A study on an open architecture CNC system with a NURBS interpolator for WEDM, *Int. J. Adv. Manuf. Technol.* 19 (9) (2002) 664-668.
- Yeo, S.H., Ngoi, B.K.A., Poh, L.S. and Hang, C., Cost-tolerance relationships for non-traditional machining processes, *Inter. J. Adv. Manuf. Technol.* 13 (1) (1997) 35-41.
- Young, R.I.M., Machine tool programming - techniques and trends, in: *Handbook of Design, Manufacturing & Automation*, John Wiley & Sons, Inc., New York, 1994, pp. 297-311.
- Yue, T.M., Dai, Y. and Lau, W.S., An examination of wire electrical discharge machining (WEDM) of  $Al_2O_3$  particulate reinforced aluminium based composites, *Mater. Manuf. Processes* 11 (3) (1996) 341-350.
- Z68300 French National Standard, Association Française de Normalization (AFNOR), *Standard d'Echange et de Transfert (SET)*, 1985.
- Zeid, I., CAD/CAM data exchange, in: *CAD/CAM Theory & Practice*, McGraw Hill, Inc., New York, 1991, pp. 442-478.



Zhang, C.R. and Liu, R.L., On CNC machining and part program preprocessing based on STEP-NC, Materials Science Forum 471-472 (2004) 326-329.

Zhao, J., Cheung, W.M. and Young, R.I.M., A consistent manufacturing data model to support virtual enterprises, Inter. J. Agile Management Systems 1 (3) (1999) 150-158.



# **Appendix I**

## **LIST OF AUTHOR'S PUBLICATIONS**

K.H. Ho, S.T. Newman and R.D. Allen, STEP-NC compliant information modelling for wire electrical discharge machining component manufacture, Proceedings I MECH E Part B J. Eng. Manuf., 219 (B10) (2005) 777-784.

Ho, K.H., Newman, S.T., Rahimifard, S. and Allen, R.D., State of the art in wire electrical discharge machining (WEDM), Inter. J. Mach. Tools Manuf. 44 (12-13) (2004) 1247-1259.

Ho, K.H., Newman, S.T., State of the art electrical discharge machining (EDM), Inter. J. Mach. Tools Manuf. 43 (13) (2003) 1287-1300.

Ho, K.H., Newman, S.T. and Allen R.D., The design of a STEP-NC compliant wire EDM CAD/CAPP/CAM system, International Conference on Flexible Automation & Intelligent Manufacturing, Bilbao, Spain, 2005.



## Appendix II

### STEP-NC PROCESS PLAN

#### GENERATED FROM WIRE SNIPs FOR EXAMPLE PART 1

```
ISO-10303-21;  
HEADER;  
FILE_DESCRIPTION();  
FILE_NAME();  
FILE_SCHEMA();  
ENDSEC;
```

```
DATA;  
#1=PROJECT('Project',#2,(#38));
```

```
#2=WORKPLAN('Workplan',(#3,#4,#5,#6,#7),$,#29,$);
```

```
#3=MACHINING_WORKINGSTEP('WS_1',$,$,#8,$);  
#4=MACHINING_WORKINGSTEP('WS_2',$,$,#9,$);  
#5=MACHINING_WORKINGSTEP('WS_3',$,$,#10,$);  
#6=MACHINING_WORKINGSTEP('WS_4',$,$,#11,$);  
#7=MACHINING_WORKINGSTEP('WS_5',$,$,#12,$);
```

```
#8=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_1',$,5.0,#15,#16,#18,#24,  
0.2,#25,#26,#27,#28);  
#9=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_2',#13,5.0,#15,#16,$,$,0.2,  
$,$,#27,#28);  
#10=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_3',#14,5.0,#15,#16,$,$,  
0.2,$,$,#27,#28);  
#11=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_4',$,5.0,#15,#16,#20,#24,  
0.2,$,$,#27,#15);  
#12=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_5',$,5.0,#15,#16,#22,#24,  
0.2,$,#26,#27,#15);
```

```
#13=CUT_THROUGH();
```

```
#14=SLUG_REMOVAL();
```

```
#15=CARTESIAN_POINT('Start_Pt',(10.0,0.0,0.0));
```

```
#16=WIRE_TOOL('wire_1',#17,0.1,0.2,160,$);  
#17=MATERIAL('Copper_Wire','CW1',$);
```

```
#18=WIRE_EDM_TECHNOLOGY($,$,true,#19);  
#19=NUMERIC_PARAMETER('RA',1.8,'MICM');
```



```

#20=WIRE_EDM_TECHNOLOGY($$,true,#21);
#21=NUMERIC_PARAMETER('RA',0.8,'MICM');

#22=WIRE_EDM_TECHNOLOGY($$,true,#23);
#23=NUMERIC_PARAMETER('RA',0.4,'MICM');

#24=WIRE_EDM_MACHINE_FUNCTIONS(true,$$,true,false,());

#25=LINEAR_STRATEGY($$);

#26=ARC_STRATEGY($$,1.0);

#27=CARTESIAN_POINT('Thread_Pt',(10.0,10.0,0.0));

#28=CARTESIAN_POINT('Tag_Pt',(9.0,0.0,0.0));

#29=SETUP('Setup_1',#30,#32,#35);
#30=AXIS2_PLACEMENT_3D('Setup_Origin',#31,$$);
#31=CARTESIAN_POINT('SP_1',(0.0,0.0,0.0));
#32=ELEMENTARY_SURFACE('Setup_Security_Plane',#33);
#33=AXIS2_PLACEMENT_3D('Setup_Position',#34,$$);
#34=CARTESIAN_POINT('Setup_1',(0.0,0.0,20.0));

#35=WORKPIECE_SETUP($$,#36,$$,$$);
#36=AXIS2_PLACEMENT_3D('Setup_Position',#37,$$);
#37=CARTESIAN_POINT('Setup_1',(-10.0,-15.0,0.0));

#38=WORKPIECE('Workpiece',#39,$$,$$,#40,$$);
#39=MATERIAL('DS21','Die Steel',$$);
#40=BLOCK('Block_1',#41,70.0,40.0,30.0);

#41=AXIS2_PLACEMENT_3D('Block_Position_1',#42,$$);
#42=CARTESIAN_POINT('WP_Pos_1',(0.0,0.0,0.0));

EDNSEC;
END-ISO-10303-21;

```



**STEP-NC PROCESS PLAN****GENERATED FROM WIRE SNIPs FOR EXAMPLE PART 2**

```

ISO-10303-21;
HEADER;
FILE_DESCRIPTION();
FILE_NAME();
FILE_SCHEMA();
ENDSEC;

DATA;
#1=PROJECT('ProjectTwo',#2,(#30));

#2=WORKPLAN('WorkplanTwo',(#3,#4,#5),$,#21,$);

#3=MACHINING_WORKINGSTEP('WS_1',$,$,#6,$);
#4=MACHINING_WORKINGSTEP('WS_2',$,$,#7,$);
#5=MACHINING_WORKINGSTEP('WS_3',$,$,#8,$);

#6=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_1',$,5.0,#11,#12,#14,#16,
    0.2,#17,#18,#19,#20);
#7=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_2',#9,5.0,#11,#12,$,$,0.2,
    $,$,#19,#20);
#8=WIRE_EDM_MACHINING_OPERATION($,$,'Mach'g_Opn_3',#10,5.0,#11,#12,$,$,0.2,
    $,#18,#19,#20);

#9=CUT_THROUGH();
#10=SLUG_REMOVAL();

#11=CARTESIAN_POINT('Start_Pt',(0.0,0.0,0.0));

#12=WIRE_TOOL('wire_1',#13,0.25,0.2,160,$);
#13=MATERIAL('Copper_Wire','CW1',$);

#14=WIRE_EDM_TECHNOLOGY($,$,true,#15);
#15=NUMERIC_PARAMETER('RA',1.8,'MICM');

#16=WIRE_EDM_MACHINE_FUNCTIONS(true,$,false,false,());

#18=LINEAR_STRATEGY($,$);

#19=CARTESIAN_POINT('Thread_Pt',(0.0,0.0,0.0));

#20=CARTESIAN_POINT('Tag_Pt',(0.0,0.0,0.0));

#21=SETUP('Setup_1',#22,#24,#27);
#22=AXIS2_PLACEMENT_3D('Setup_Origin',#23,$,$);
#23=CARTESIAN_POINT('SP_1',(0.0,0.0,0.0));
#24=ELEMENTARY_SURFACE('Setup_Security_Plane',#25);

```



```
#25=AXIS2_PLACEMENT_3D('Setup_Position',#26,$,$);  
#26=CARTESIAN_POINT('Setup_1',(0.0,0.0,0.0));
```

```
#27=WORKPIECE_SETUP($,#28,$,$,$);  
#28=AXIS2_PLACEMENT_3D('Setup_Position',#29,$,$);  
#29=CARTESIAN_POINT('Setup_1',(0.0,0.0,0.0));
```

```
#30=WORKPIECE('WorkpieceTwo',#31,$,$,$,#32,$);  
#31=MATERIAL('DS21','Die Steel',$);  
#32=BLOCK('Block_1',#33,20.0,10.0,10.0);
```

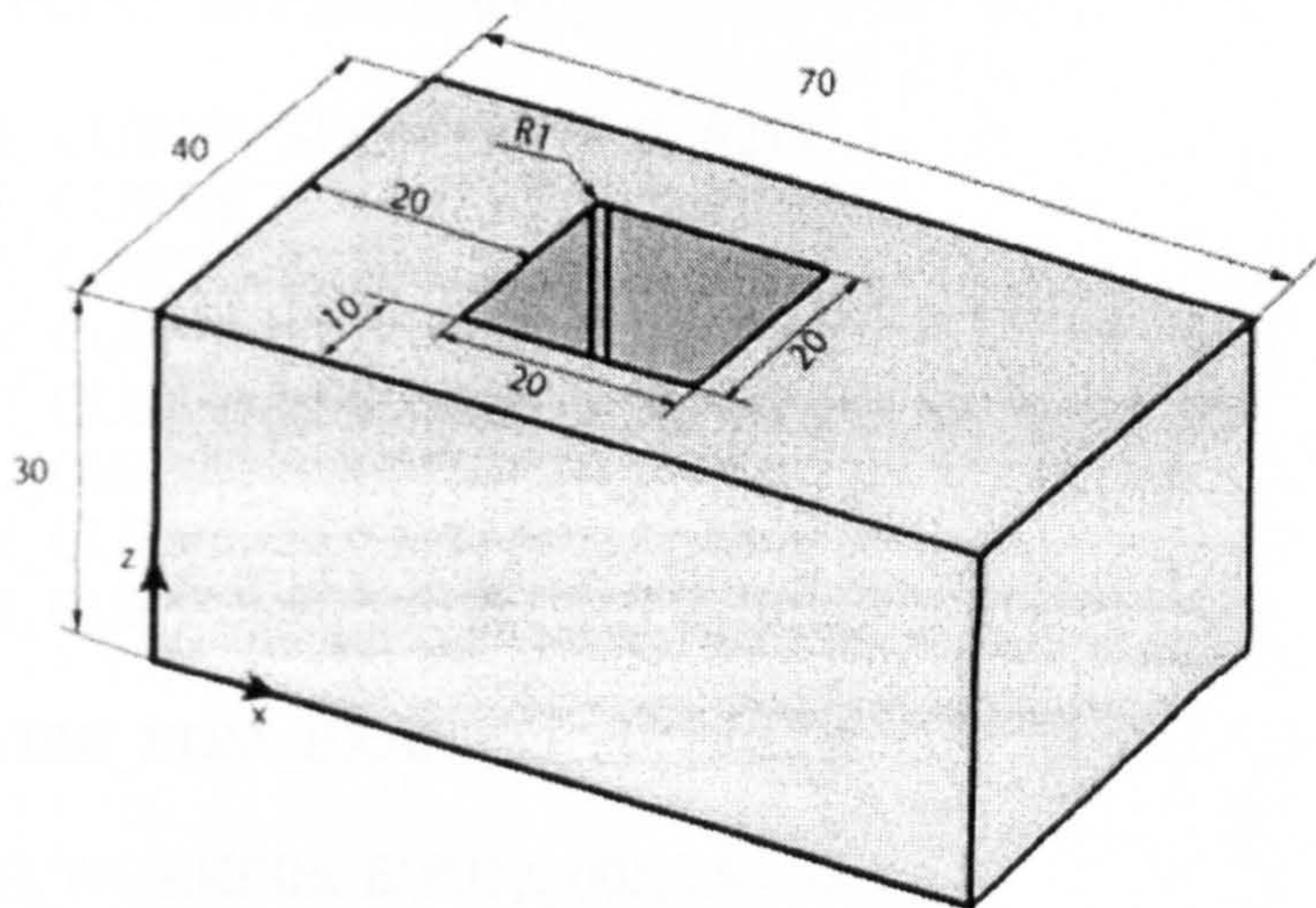
```
#33=AXIS2_PLACEMENT_3D('Block_Position_1',#34,$,$);  
#34=CARTESIAN_POINT('WP_Pos_1',(0.0,0.0,0.0));
```

```
EDNSEC;  
END-ISO-10303-21;
```



## Appendix III

### CASE STUDY BASED ON THE EXAMPLE PART 1 PROVIDED IN ISO/DIS 14649-13



ISO-10303-21;  
HEADER;

FILE\_DESCRIPTION(

/\* DESCRIPTION \*/ ('THIS FILE CONTAINS THE STEP-NC FILE OF A WIRE-EDM  
MANUFACTURING'),  
/\* IMPLEMENTATION\_LEVEL \*/ ('2;1');

FILE\_NAME(

/\* NAME \*/ 'WIRE\_EDM\_EXAMPLE',  
/\* TIME\_STAMP \*/ '2003-02-28T14:17:26+01:00',  
/\* AUTHOR \*/ ('GABOR ERDOS'),  
/\* ORGANIZATION \*/ ('EPFL-ICAP-LICP, LAUSANNE SWITZERLAND');

FILE\_SCHEMA (('MACHINING\_SCHEMA','WIRE\_EDM\_SCHEMA'));  
ENDSEC;

DATA;

#10=ARC\_STRATEGY(\$,\$,1.);  
#11=SLUG\_REMOVAL();  
#12=CUT\_THROUGH();

#13=CIRCLE('CIRCLE\_009',#83,1.);  
#14=CIRCLE('CIRCLE\_010',#84,1.);  
#15=CIRCLE('CIRCLE\_011',#85,1.);  
#16=CIRCLE('CIRCLE\_012',#86,1.);

#17=TRIMMED\_CURVE('TRIMMED\_CURVE\_009',#13,(#55),(#56),.T.,\$);



```
#18=TRIMMED_CURVE('TRIMMED_CURVE_010',#14,(#60),(#61),.T.,$);
#19=TRIMMED_CURVE('TRIMMED_CURVE_011',#15,(#65),(#66),.T.,$);
#20=TRIMMED_CURVE('TRIMMED_CURVE_012',#16,(#70),(#71),.T.,$);
```

```
#21=POLYLINE('PLINE_009',(#52,#53));
#22=POLYLINE('PLINE_010',(#57,#58));
#23=POLYLINE('PLINE_011',(#62,#63));
#24=POLYLINE('PLINE_012',(#67,#68));
```

```
#25=COMPOSITE_CURVE_SEGMENT($,.T.,#21);
#26=COMPOSITE_CURVE_SEGMENT($,.T.,#17);
#27=COMPOSITE_CURVE_SEGMENT($,.T.,#22);
#28=COMPOSITE_CURVE_SEGMENT($,.T.,#18);
#29=COMPOSITE_CURVE_SEGMENT($,.T.,#23);
#30=COMPOSITE_CURVE_SEGMENT($,.T.,#19);
#31=COMPOSITE_CURVE_SEGMENT($,.T.,#24);
#32=COMPOSITE_CURVE_SEGMENT($,.T.,#20);
```

```
#33=PROJECT('WIRE_EDM_EXAMPLE',#39,(#34));
```

```
#34=WORKPIECE('WORKPIECE',#35,0.005,$,$,#38,$);
```

```
#35=MATERIAL('ST221','COLD DIE STEEL',$);
#36=MATERIAL('ST234','COBRA CUT A',$);
#37=MATERIAL(",",$);
```

```
#38=BLOCK('BLOCK_001',#82,40.,30.,70.);
```

```
#39=WORKPLAN('WP',(#40,#41,#42,#43,#44),#115,#117);
```

```
#40=MACHINING_WORKINGSTEP('WS_01',$,#89,#91);
#41=MACHINING_WORKINGSTEP('WS_02',$,#89,#92);
#42=MACHINING_WORKINGSTEP('WS_03',$,#89,#93);
#43=MACHINING_WORKINGSTEP('WS_04',$,#89,#94);
#44=MACHINING_WORKINGSTEP('WS_05',$,#89,#95);
```

```
#45=TOLERANCED_LENGTH_MEASURE(30.,$,0.,0.);
#46=TOLERANCED_LENGTH_MEASURE(1.,$,0.,0.);
```

```
#47=CARTESIAN_POINT('FEATORIGIN',(20.,10.,30.));
#48=CARTESIAN_POINT('WORKPIECE_BBBOX_LOCATION',(-10.,-15.,0.));
#49=CARTESIAN_POINT('CUT_START_PT',(10.,0.,0.));
#50=CARTESIAN_POINT('THREAD_PT',(10.,10.,0.));
#51=CARTESIAN_POINT('CUT_END_PT',(9.,0.,0.));
#52=CARTESIAN_POINT('CARTESIAN_POINT_001_OF_PLINE_009',(1.,20.,0.));
#53=CARTESIAN_POINT('CARTESIAN_POINT_002_OF_PLINE_009',(19.,20.,0.));
#54=CARTESIAN_POINT('CENTRE_POINT_OF_CIRCLE_009',(19.,19.,0.));
#55=CARTESIAN_POINT('START_POINT_OF_TRIMMEDCURVE_009',(19.,20.,0.));
#56=CARTESIAN_POINT('END_POINT_OF_TRIMMEDCURVE_009',(20.,19.,0.));
#57=CARTESIAN_POINT('CARTESIAN_POINT_001_OF_PLINE_010',(20.,19.,0.));
```



```

#58=CARTESIAN_POINT('CARTESIAN_POINT_002_OF_PLINE_010',(20.,1.,0.));
#59=CARTESIAN_POINT('CENTRE_POINT_OF_CIRCLE_010',(19.,1.,0.));
#60=CARTESIAN_POINT('START_POINT_OF_TRIMMEDCURVE_010',(20.,1.,0.));
#61=CARTESIAN_POINT('END_POINT_OF_TRIMMEDCURVE_010',(19.,0.,0.));
#62=CARTESIAN_POINT('CARTESIAN_POINT_001_OF_PLINE_011',(19.,0.,0.));
#63=CARTESIAN_POINT('CARTESIAN_POINT_002_OF_PLINE_011',(1.,0.,0.));
#64=CARTESIAN_POINT('CENTRE_POINT_OF_CIRCLE_011',(1.,1.,0.));
#65=CARTESIAN_POINT('START_POINT_OF_TRIMMEDCURVE_011',(1.,0.,0.));
#66=CARTESIAN_POINT('END_POINT_OF_TRIMMEDCURVE_011',(0.,1.,0.));
#67=CARTESIAN_POINT('CARTESIAN_POINT_001_OF_PLINE_012',(0.,1.,0.));
#68=CARTESIAN_POINT('CARTESIAN_POINT_002_OF_PLINE_012',(0.,19.,0.));
#69=CARTESIAN_POINT('CENTRE_POINT_OF_CIRCLE_012',(1.,19.,0.));
#70=CARTESIAN_POINT('START_POINT_OF_TRIMMEDCURVE_012',(0.,19.,0.));
#71=CARTESIAN_POINT('END_POINT_OF_TRIMMEDCURVE_012',(1.,20.,0.));
#72=CARTESIAN_POINT('SO1',(0.,0.,20.));

```

```

#73=DIRECTION('FEATZAXIS',(0.,0.,1.));
#74=DIRECTION('FEATXAXIS',(1.,0.,0.));
#75=DIRECTION('AXIS_Z_OF_BLOCK_001',(1.,0.,0.));
#76=DIRECTION('AXIS_X_OF_BLOCK_001',(0.,1.,0.));
#77=DIRECTION('Z_AXIS_OF_CIRCLE_009',(0.,0.,-1.));
#78=DIRECTION('Z_AXIS_OF_CIRCLE_010',(0.,0.,-1.));
#79=DIRECTION('Z_AXIS_OF_CIRCLE_011',(0.,0.,-1.));
#80=DIRECTION('Z_AXIS_OF_CIRCLE_012',(0.,0.,-1.));

```

```

#81=AXIS2_PLACEMENT_3D('FEAT_FRAME',#47,#73,#74);
#82=AXIS2_PLACEMENT_3D('POSITION_OF_BLOCK_001',#48,#75,#76);
#83=AXIS2_PLACEMENT_3D('POSTION_OF_CIRCLE_009',#54,#77,$);
#84=AXIS2_PLACEMENT_3D('POSTION_OF_CIRCLE_010',#59,#78,$);
#85=AXIS2_PLACEMENT_3D('POSTION_OF_CIRCLE_011',#64,#79,$);
#86=AXIS2_PLACEMENT_3D('POSTION_OF_CIRCLE_012',#69,#80,$);
#87=AXIS2_PLACEMENT_3D('SECPLANE_FRAME',#72,$,$);

```

```

#88=COMPOSITE_CURVE('POCKET',(#25,#26,#27,#28,#29,#30,#31,#32),.F.);

```

```

#89=GENERAL_OUTSIDE_PROFILE('WORK1',#34,(#91,#92,#93,#94,#95),#81,#45,#46,$,
$, $, #88, $, $);

```

```

#90=WIRE_TOOL('WIRE1',#36,0.1,0.2,160.,$);

```

```

#91=WIRE_EDM_MACHINING_OPERATION($,$,'ROUGHING',$,10.,#49,#90,#100,
#114,0.01,#96,#97,#50,#51);
#92=WIRE_EDM_MACHINING_OPERATION($,$,'CUT_THROUGH',#12,10.,#49,#90,#9
9,$,0.01,$,$,#50,#51);
#93=WIRE_EDM_MACHINING_OPERATION($,$,'SLUG_REMOVAL',#11,10.,#49,#90,#
99,$,1.,$,$,#50,#51);
#94=WIRE_EDM_MACHINING_OPERATION($,$,'FINISHING',$,10.,#49,#90,#98,#114,0.
1,$,$,#50,#49);
#95=WIRE_EDM_MACHINING_OPERATION($,$,'SURFACE_FINISHING',$,10.,#49,
#90,#101,#114,0.01,$,#10,#50,#49);

```



```

#96=LINEAR_STRATEGY($,$);
#97=LINEAR_STRATEGY($,$);

#98=WIRE_EDM_TECHNOLOGY(0.,TCP.,$,$,#103,#108,#109,#110));
#99=WIRE_EDM_TECHNOLOGY(0.,TCP.,$,$,());
#100=WIRE_EDM_TECHNOLOGY(0.,$,$,$,($102,#105,#107,#106));
#101=WIRE_EDM_TECHNOLOGY(0.,TCP.,$,$,($104,#111,#112,#113));

#102=DESCRIPTIVE_PARAMETER('ID','Q2');
#103=DESCRIPTIVE_PARAMETER('ID','Q3');
#104=DESCRIPTIVE_PARAMETER('ID','Q8');

#105=NUMERIC_PARAMETER('RA',1.8,'MICM');
#106=NUMERIC_PARAMETER('TKM',10.,'MICM');
#107=NUMERIC_PARAMETER('TE',10.,'MICM');
#108=NUMERIC_PARAMETER('RA',0.8,'MICM');
#109=NUMERIC_PARAMETER('TKM',6.,'MICM');
#110=NUMERIC_PARAMETER('TE',6.,'MICM');
#111=NUMERIC_PARAMETER('RA',0.4,'MICM');
#112=NUMERIC_PARAMETER('TKM',3.,'MICM');
#113=NUMERIC_PARAMETER('TE',3.,'MICM');

#114=WIRE_EDM_MACHINE_FUNCTIONS(.T.,$,.T.,.F.,());

#115=CHANNEL('CHANEL_1');

#116=PLANE($,#87);

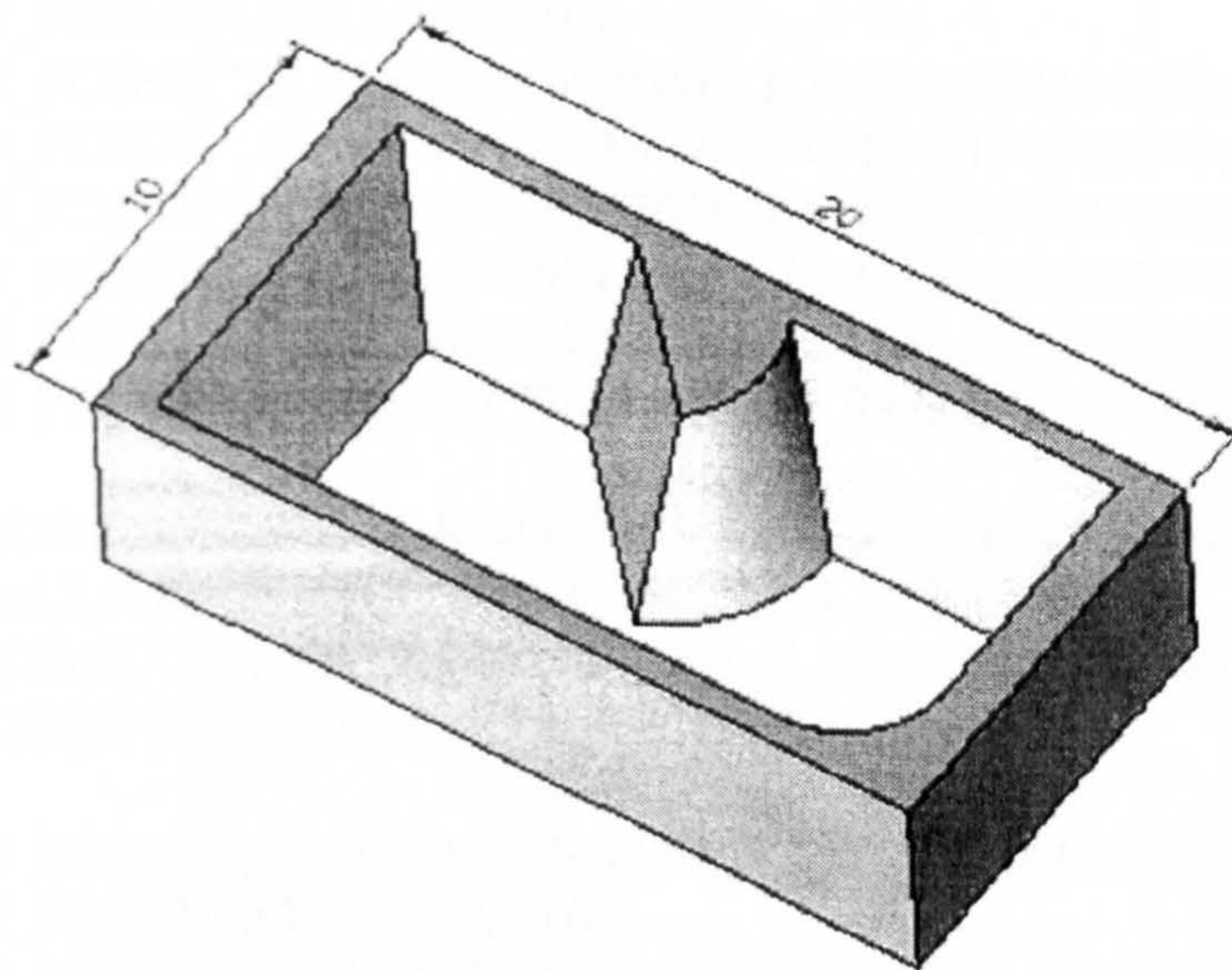
#117=SETUP('SETUP',$,#116,());

ENDSEC;
END-ISO-10303-21;

```



## CASE STUDY BASED ON THE EXAMPLE PART 2 PROVIDED IN ISO/DIS 14649-13



ISO-10303-21;  
HEADER;

FILE\_DESCRIPTION(  
/\* DESCRIPTION \*/ (  
'THIS FILE CONTAINS THE STEP-NC FILE OF A WIRE-EDM MANUFACTURING'),  
/\* IMPLEMENTATION\_LEVEL \*/ '2;1');

FILE\_NAME(  
/\* NAME \*/ 'SAMPLE WITH RULED SURFACESR',  
/\* TIME\_STAMP \*/ '2003-02-28T13:09:21+02:00',  
/\* AUTHOR \*/ ('WILLY MAEDER'),  
/\* ORGANIZATION \*/ ('CADCAMATION SA, ONEX-GENEVA, SWITZERLAND'),  
/\* PREPROCESSOR\_VERSION \*/ 'ST-DEVELOPER V8',  
/\* ORIGINATING\_SYSTEM \*/ '',  
/\* AUTHORISATION \*/ '');

FILE\_SCHEMA (('MACHINING\_SCHEMA','WIRE\_EDM\_SCHEMA'));  
ENDSEC;

DATA;  
#2=CARTESIAN\_POINT("(-50.0,30.0,20.0));  
#3=CARTESIAN\_POINT("(0.0,30.0,20.0));  
#4=CARTESIAN\_POINT("(-46.0,26.0,0.0));  
#5=CARTESIAN\_POINT("(-3.762857145299775,26.0,0.0));  
  
#6=B\_SPLINE\_SURFACE\_WITH\_KNOTS("1,1,((#2,#4),(#3,#5)),UNSPECIFIED.,.F.,.F.,  
.U.,(2,2),(2,2),(-50.0,0.0),(0.0,1.0),UNSPECIFIED.);  
  
#7=CARTESIAN\_POINT("(8.786796564403542,8.786796564403606,20.0));



```

#8=CARTESIAN_POINT(",(6.935595340170893,10.637997788636259,20.0));
#9=CARTESIAN_POINT(",(3.720779449950078,14.827639903211258,20.0));
#10=CARTESIAN_POINT(",(0.689306233719310,22.146263655806401,20.0));
#11=CARTESIAN_POINT(",(-2.645847E-015,27.382006122008541,20.0));
#12=CARTESIAN_POINT(",(0.0,30.0,20.0));
#13=CARTESIAN_POINT(",(8.955855216991068,3.295244424414630,0.0));
#14=CARTESIAN_POINT(",(6.625202790118829,5.131868128801239,0.0));
#15=CARTESIAN_POINT(",(2.447738076337918,9.418653244101920,0.0));
#16=CARTESIAN_POINT(",(-1.940637859416365,17.251877607654784,0.0));
#17=CARTESIAN_POINT(",(-3.414762067389234,23.053144355453618,0.0));
#18=CARTESIAN_POINT(",(-3.763871791715616,25.999879797732245,0.0));

#19=B_SPLINE_SURFACE_WITH_KNOTS(",3,1,((#7,#13),(#8,#14),(#9,#15),(#10,#16),
    (#11,#17),(#12,#18)),.UNSPECIFIED.,.F.,.F.,.U.,(4,1,1,4),(2,2),
    (-3.926990816987240,-3.665191429188091,-3.403392041388941,
    -3.141592653589792),(0.0,1.0),.UNSPECIFIED.);

#20=CARTESIAN_POINT(",(8.786796564403602,8.786796564403602,20.0));
#21=CARTESIAN_POINT(",(30.0,30.0,20.0));
#22=CARTESIAN_POINT(",(8.955855216991086,3.295244424414616,0.0));
#23=CARTESIAN_POINT(",(31.656854249492397,26.0,0.0));

#24=B_SPLINE_SURFACE_WITH_KNOTS(",1,1,((#20,#22),(#21,#23)),.UNSPECIFIED.,
    .F.,.F.,.U.,(2,2),(2,2),(-30.0,0.0),(0.0,1.0),.UNSPECIFIED.);

#25=CARTESIAN_POINT(",(30.0,30.0,20.0));
#26=CARTESIAN_POINT(",(70.0,30.0,20.0));
#27=CARTESIAN_POINT(",(31.656854249492397,26.0,0.0));
#28=CARTESIAN_POINT(",(66.0,26.0,0.0));

#29=B_SPLINE_SURFACE_WITH_KNOTS(",1,1,((#25,#27),(#26,#28)),.UNSPECIFIED.,
    .F.,.F.,.U.,(2,2),(2,2),(-40.0,0.0),(0.0,1.0),.UNSPECIFIED.);

#30=CARTESIAN_POINT(",(70.0,30.0,20.0));
#31=CARTESIAN_POINT(",(70.0,-50.0,20.0));
#32=CARTESIAN_POINT(",(66.0,26.0,0.0));
#33=CARTESIAN_POINT(",(66.0,-46.0,0.0));

#34=B_SPLINE_SURFACE_WITH_KNOTS(",1,1,((#30,#32),(#31,#33)),.UNSPECIFIED.,
    .F.,.F.,.U.,(2,2),(2,2),(-80.0,0.0),(0.0,1.0),.UNSPECIFIED.);

#35=CARTESIAN_POINT(",(70.0,-50.0,20.0));
#36=CARTESIAN_POINT(",(-20.0,-50.0,20.0));
#37=CARTESIAN_POINT(",(66.0,-46.0,0.0));
#38=CARTESIAN_POINT(",(-20.0,-46.0,0.0));

#39=B_SPLINE_SURFACE_WITH_KNOTS(",1,1,((#35,#37),(#36,#38)),.UNSPECIFIED.,
    .F.,.F.,.U.,(2,2),(2,2),(-90.0,0.0),(0.0,1.0),.UNSPECIFIED.);

#40=CARTESIAN_POINT(",(-50.0,-20.0,20.0));

```



```

#41=CARTESIAN_POINT("(-50.0,30.0,20.0));
#42=CARTESIAN_POINT("(-46.0,-20.0,0.0));
#43=CARTESIAN_POINT("(-46.0,26.0,0.0));

#44=B_SPLINE_SURFACE_WITH_KNOTS(",1,1,((#40,#42),(#41,#43)),.UNSPECIFIED.,
.F.,.F.,.U.,(2,2),(2,2),(-50.0,0.0),(0.0,1.0),.UNSPECIFIED.);

#45=CARTESIAN_POINT("(-50.0,-20.0,20.0));
#46=CARTESIAN_POINT("(-50.0,-22.243994752564106,20.0));
#47=CARTESIAN_POINT("(-49.494332216275893,-26.731874096003608,20.0));
#48=CARTESIAN_POINT("(-47.256861435762637,-33.126216647277602,20.0));
#49=CARTESIAN_POINT("(-43.652618263109133,-38.862332356046295,20.0));
#50=CARTESIAN_POINT("(-38.862332356046380,-43.652618263109090,20.0));
#51=CARTESIAN_POINT("(-33.126216647277673,-47.256861435762580,20.0));
#52=CARTESIAN_POINT("(-26.731874096003700,-49.494332216275879,20.0));
#53=CARTESIAN_POINT("(-22.243994752564198,-50.0,20.0));
#54=CARTESIAN_POINT("(-20.0,-50.0,20.0));
#55=CARTESIAN_POINT("(-46.0,-20.0,0.0));
#56=CARTESIAN_POINT("(-46.0,-21.940717585790633,0.0));
#57=CARTESIAN_POINT("(-45.561751785744534,-25.836183427878151,0.0));
#58=CARTESIAN_POINT("(-43.622623050258596,-31.375547320925282,0.0));
#59=CARTESIAN_POINT("(-40.498899405998614,-36.347490590759556,0.0));
#60=CARTESIAN_POINT("(-36.347490590759676,-40.498899405998628,0.0));
#61=CARTESIAN_POINT("(-31.375547320925357,-43.622623050258554,0.0));
#62=CARTESIAN_POINT("(-25.836183427878254,-45.561751785744747,0.0));
#63=CARTESIAN_POINT("(-21.940717585790722,-46.0,0.0));
#64=CARTESIAN_POINT("(-20.0,-46.0,0.0));

#65=B_SPLINE_SURFACE_WITH_KNOTS(",3,1,((#45,#55),(#46,#56),(#47,#57),(#48,
#58),(#49,#59),(#50,#60),(#51,#61),(#52,#62),(#53,#63),(#54,#64)),.UNSPECIFIED.,
.F.,.F.,.U.,(4,1,1,1,1,1,4),(2,2),(3.141592653589792, 3.365992128846206,
3.590391604102619, 3.814791079359032, 4.039190554615447, 4.263590029871861,
4.487989505128275, 4.712388980384688), (0.0,1.0),.UNSPECIFIED.);

#110=DESCRIPTIVE_PARAMETER('TKM','+/-10 MICROM');
#111=DESCRIPTIVE_PARAMETER('TE','10-15 MICROM');

#112=WIRE_EDM_TECHNOLOGY(0.,$,,$,($113,#111,#110));
#113=NUMERIC_PARAMETER('RA',1.8,'MICROM');

#114=LINEAR_STRATEGY($,$);

#115=WIRE_EDM_MACHINE_FUNCTIONS(.T.,2.3,.F.,.F.,0);

#116=WIRE_TOOL('WIRE TOOL',#120,0.25,0.,0.,$);

#117=PROJECT('SAMPLE 2',#121,($118));

#118=WORKPIECE('WORKPIECE',#119,$,$,$,$,$);

```



#119=MATERIAL('','COLD DIE STEEL',\$);

#120=MATERIAL('','COBRA CUT',\$);

#121=WORKPLAN('WORKPLAN1',(#122),\$,\$);

#122=MACHINING\_WORKINGSTEP('STEP1',\$,#125,#163);

#125=REGION\_SURFACE\_LIST('REGION1',#18,(#163),\$(#6,#19,#24,#29,#34,#39,#44,  
#65));

#163=WIRE\_EDM\_MACHINING\_OPERATION(\$,\$,'OPER1',\$,\$,#94,#116,#112,#115,2.,\$,  
#114, #95, #96);

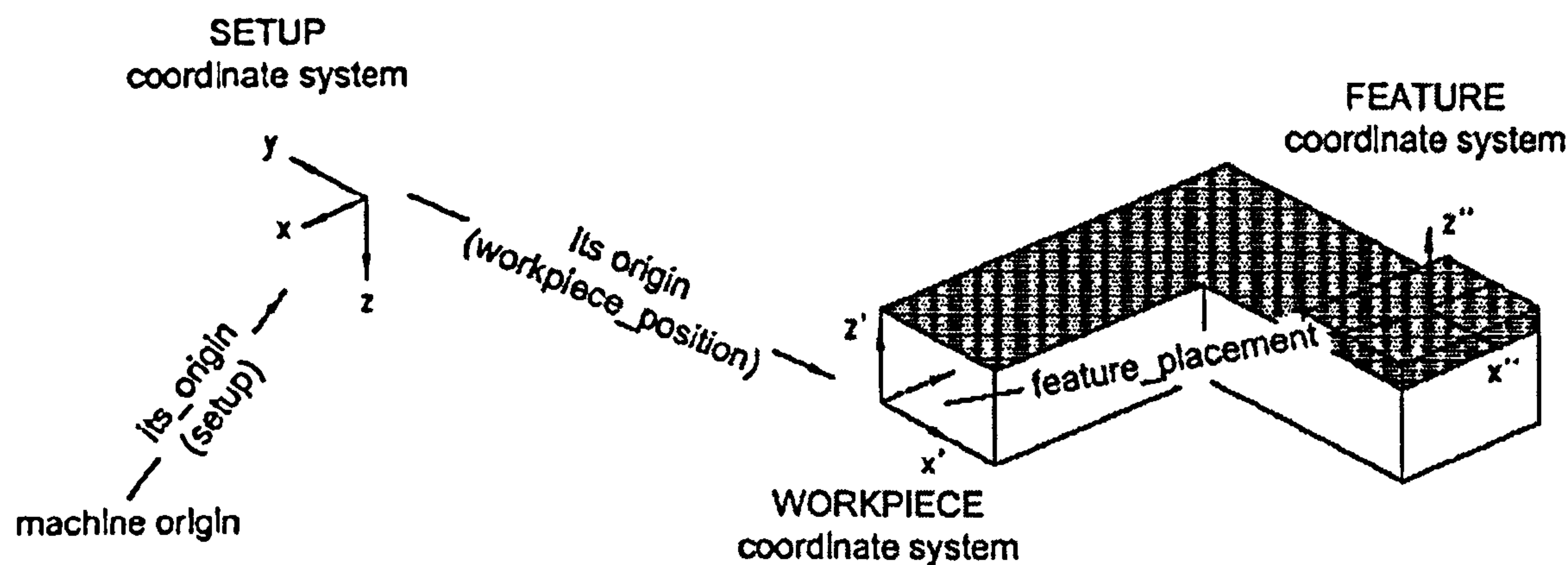
ENDSEC;

END-ISO-10303-21;



# Appendix IV

## STEP-NC (ISO 14649-10) ENTITY SETUP



```
STEP-NC setup entity
ENTITY setup;
its_id: identifier;
its_origin: OPTIONAL axis2_placement_3d;
its_secplane: elementary_surface;
its_workpiece_setup: LIST [0:?] OF workpiece_setup;
(*)
Informal proposition:
If its_origin is not set, the default for the origin
of the setup is identical with the machine origin.
*)
END_ENTITY;
```

Description	
its_id:	The identification of the setup.
its_origin:	Position and orientation of the setup's cartesian coordinate system relative to the machine coordinate system.
its_secplane:	The security plane for the whole setup. On or above this plane, i. e. for z values greater than those of the elementary_surface, a safe movement of the tool without danger of collision is possible. The dimensions given are relative coordinates as measured from the origin of the setup.
its_workpiece_setup:	Each workpiece which is included within the setup and which will be machined within the respective workplan



## Appendix V

### NC PART PROGRAM GENERATED FROM FANUC PC FAPT CUT I

```
%  
N010 O0001  
N020 G00 G40 G50  
N030 G10 P1 X1 Y1 Z4 U3 V190 W25 I10 J10 K1 A30 C10 E7 Q0 L48 (D2.A2/30/.10/3H)  
N040 G11 P1 X1 I0  
N050 G10 P2 X1 Y3 Z3 U2 V200 W40 I0 J0 K2 A40 C13 E2 Q0 L290 (D2.A2/ 30/ .10/ 32)  
N060 G11 P2 X1 I0  
N070 G10 P3 X2 Y3 U40 V100 W33 K3 A40 C13 E2 Q0 L920 (D2.A2/ 30/ .10/ 33)  
N080 G11 P3 X1 I0  
N090 G90  
N100 G10 P1 R0.1060  
N110 G10 P2 R0.0710  
N120 G10 P3 R0.0560  
N130 G10 P0 R0.1060  
N140 (FIG#1 / CONTOUR – 1)  
N150 M37 B30  
N160 M89  
N170 S1 D1 G04 X2  
N180 G92 X10 Y10  
N190 G90 G01 G41 X10 Y0  
N200 X19  
N210 G03 X20 Y1 J1  
N220 G01 Y19  
N230 G03 X19 Y20 I-1  
N240 G01 X1  
N250 G03 X0 Y19 J-1  
N260 G01 Y1  
N270 G03 X1 Y0 I1  
N280 G01 X9  
N290 M01  
N300 X10  
N310 M00  
N320 G40 Y10  
N330 M00  
N340 (FIG#1 / CONTOUR – 2)  
N350 G90 G00 X10 Y10  
N360 M38 B30 H0  
N370 M88  
N380 S2 D2 G04 X2  
N390 G92 X10 Y10  
N400 G90 G01 G41 X10 Y0
```



N410 X19  
N420 G03 X20 Y1 J1  
N430 G01 Y19  
N440 G03 X19 Y20 I-1  
N450 G01 X1  
N460 G03 X0 Y19 J-1  
N470 G01 Y1  
N480 G03 X1 Y0 I1  
N490 G01 X10  
N500 G40 Y10  
N510 (FIG#1/ CONTOUR – 3)  
N520 G90 G00 X10 Y10  
N530 M38 B30 H0  
N540 M88  
N550 S3 D3 G04 X2  
N560 G92 X10 Y10  
N570 G90 G01 G41 X10 Y0  
N580 X19  
N590 G03 X20 Y1 J1  
N600 G01 Y19  
N610 G03 X19 Y20 I-1  
N620 G01 X1  
N630 G03 X0 Y19 J-1  
N640 G01 Y1  
N650 G03 X1 Y0 I1  
N660 G01 X10  
N670 G40 Y10  
N680 /M50  
N690 G90 G00 X10 Y10  
N700 M30  
%

---

Total Time of Rapid: 00:00'00"  
Total Time of Cutting: 05:49'03"  
Total Length: 294.85  
Max. Wire Inclination Angle: 0.0  
Wire Cut Start Points: X10 Y10



# NC PART PROGRAM GENERATED FROM PEPS SOLID CUT

```

%
L110 /FIG
N10 (METRIC)
N20 (H99 RESERVED - PEPS)
N30 G71
N40 Z1=0.00
N50 Z2=15.00
N60 Z5=30.00
N70 G90
N80 G92 X0.0 Y0.0
N90 G00 X10.0 Y10.0 U0.0 V0.0
N100 (ROUGH CUT #1 FIG_000)
N110 M20
N120 M78
N130 M80
N140 M82
N150 M84
N160 M89
N170 M101
N180 E1 F1.0 H1
N190 G01 G41 X10.0 Y0.0 M90
N200 G01 X19.0 Y0.0
N210 G03 X20.0 Y1.0 I0.0 J1.0
N220 G01 Y19.0
N230 G03 X19.0 Y20.0 I-1.0 J0.0
N240 G01 X1.0
N250 G03 X0.0 Y19.0 I0.0 J-1.0
N260 G01 Y1.0
N270 G03 X1.0 Y0.0 I1.0 J0.0
N280 G01 X9.0
N290 M01
N300 M78
N310 M80
N320 M82
N330 M84
N340 G01 X10.0 Y0.0
N350 G03 X11.0 Y1.0 I0.0 J1.0
N360 G01 Y10.0
N370 G01 G40 X10.0 U0.0 V0.0
N380 M91
N390 G04 X13.0
N400 (TRIM CUT #2 FIG_000)
N410 M88
N420 E2 F2.0 H2
N430 G01 G41 X10.0 Y0.0 M90

```



N440 G01 X19.0 Y0.0  
N450 G03 X20.0 Y1.0 I0.0 J1.0  
N460 G01 Y19.0  
N470 G03 X19.0 Y20.0 I-1.0 J0.0  
N480 G01 X1.0  
N490 G03 X0.0 Y19.0 I0.0 J-1.0  
N500 G01 Y1.0  
N510 G03 X1.0 Y0.0 I1.0 J0.0  
N520 G01 X10.0  
N530 G03 X11.0 Y1.0 I0.0 J1.0  
N540 G01 Y10.0  
N550 G01 G40 X10.0 U0.0 V0.0  
N560 M91  
N570 (TRIM CUT #3 FIG\_000)  
N580 M88  
N590 E3 F3.0 H3  
N600 G01 G41 X10.0 Y0.0 M90  
N610 G01 X19.0 Y0.0  
N620 G03 X20.0 Y1.0 I0.0 J1.0  
N630 G01 Y19.0  
N640 G03 X19.0 Y20.0 I-1.0 J0.0  
N650 G01 X1.0  
N660 G03 X0.0 Y19.0 I0.0 J-1.0  
N670 G01 Y1.0  
N680 G03 X1.0 Y0.0 I1.0 J0.0  
N690 G01 X10.0  
N700 G03 X11.0 Y1.0 I0.0 J1.0  
N710 G01 Y10.0  
N720 G01 G40 X10.0 U0.0 V0.0  
N730 M91  
N740 M21  
N750 M02  
%

---

Machine Model:	FX
Part Number:	0505
Wire Type:	Wire Dia. 0.10mm, 0.004"
Thickness:	30.0
Operation:	Opn Example
Start Point:	X0.0 Y0.0

PROFILE of Fig\_000

Taper Angle:	0.0
Number of Cuts:	3
Reverse Cutting:	Not Active
Start Hole Position:	X 10.0 Y 10.0
Figure Type:	Die



H1 (-0.0) E1 F1 Comment for cut: ROUGH CUT #1 FIG\_000  
H2 (-0.0) E2 F2 Comment for cut: TRIM CUT #2 FIG\_000  
H3 (-0.0) E3 F3 Comment for cut: TRIM CUT #3 FIG\_000

Length of machining incl. final cuts 299.57 mm  
Estimated Cycle Time 149.79 min



Appendix V

G Code List

Code	Description	Format
G04	Dwell	G04 P_, G04 X_
G92	Abso. Coord. Sys. Preset	G92 X_ Y_ I_ J_ P_ B_ R_
G93	Local Position Setting	G93 X_ Y_
G28	Return To Machine Zero Point	G28 X_ Y_ U_ V_
G29	Return From Reference Point	G29 X_ Y_ U_ V_
G30	Return To 2, 3, 4th Reference Point	G30 P_ X_ Y_ U_ V_
G32	Reference Point Setting - Type A	G32 P_
G33	Reference Point Setting - Type B	G33 P_ X_ Y_ U_ V_
G53	Position In Machine Coord. Sys.	G53 X_ Y_ U_ V_
G10	Setting Offset Or Condition	G10 P_ R_, G10 P_ X_ Y_ Z_ U_ V_ W_...
G00	Rapid Traverse	G00 X_ Y_ U_ V_
G01	Linear Interpolation	G01 X_ Y_ U_ V_
G02	Circular Interpolation (CW)	G02 X_ Y_ I_ J_ U_ V_ K_ L_
G03	Circular Interpolation (CCW)	G03 X_ Y_ I_ J_ U_ V_ K_ L_
G17	Specifying The X-Y Plane	G17
G90	Absolute Programming	G90
G91	Incremental Programming	G91
G22	Stored Stroke Limit On	G22 X_ Y_ I_ J_
G23	Stored Stroke Limit Off	G23
G94	Constant Feed	G94 X_ Y_ F_
G95	Servo Feed	G95 X_ Y_

M Code List

Code	Description	Code	Description
M00	Unconditional Program Stop	M27	Corner Control On (Roughing)
M01	Optional Program Stop	M28	Corner Control On (Skimming)
M02	Program End	M29	Corner Control Function Off
M30	Program End And Rewind	M37	Corner Control On Except G40 (Roughing)
M04	Dwell (M04 P_)	M38	Corner Control On Except G40 (Skimming)
M13	Setting Feedrate Override (M13 P_)	M56	AWR Off Time Control Function Off
M15	Selection of Tapering Mode (M15 P_)	M57	AWR Off Time Control Function On
M31	Reset Machining Timer	M88	Approach Control Function Off
M32	Hold Water At Program End	M89	Approach Control Function On
M70	Retrace Wire Path To Start Point	M92	Upper Flush Off
M72	Start Point Of Cut Monitor	M93	Upper Flush On
M96	Reverse Copy End	M94	Lower Flush Off
M97	Reverse Copy Start	M95	Lower Flush On
M98	Subprogram Call	M161	WTA Control Off
M99	Subprogram End	M162	WTA Control On
M135	Discharge Position M70 Off	M165	Skim Off
M136	Discharge Position M70 On	M166	Skim On