

## **STEP-compliant NC research: the search for intelligent CAD/CAPP/CAM/CNC integration**

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Since the first generation of Numerically Controlled (NC) machine tools was developed in the 1950s, there have been many developments which make today's NC machines completely unrecognizable from their early ancestors. Further developments, however, are now being significantly limited by the current programming language (ISO6983 or RS274D) that has been supporting NC manufacture since day one. Today a new standard, informally known as STEP-NC, is being used as the basis for development of the next generation of Computer Numerically Controlled (CNC) controller. This new standard is ISO 14649 and ISO 10303 AP 238. This standard gives CAM and CNC vendors the opportunity to integrate the capabilities of CAD/CAM systems with a new breed of intelligent CNC controllers, which have bi-directional communication of information representing standardized geometric and manufacturing data. This paper presents a comprehensive review of STEP-NC developments for a range of CNC processes. These developments include some major projects collaborated at the international level as well as those carried out by different groups of researchers in countries such as Germany, Switzerland, UK, Korea, USA and New Zealand. This paper also tries to portray a futuristic view of STEP-NC applications for CAD, CAPP, CAM and CNC integration, identifies the issues and challenges for STEP-NC, and provides a vision of a STEP-NC-compliant process chain supported by a product and manufacturing model.

*Keywords:* CAD; CAPP; CAM; CNC; STEP; STEP-NC

### **1. Introduction**

From the design of the first Numerically Controlled (NC) machine, the dream of automatic manufacture of discrete components has been sought. Over the last 50 years, machine tools have evolved from simple machines with controllers that had

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no memory, driven by punched tape, to today's highly sophisticated Computer Numerically Controlled (CNC) multi-process workstations. These workstations have capabilities such as multi-axis control, adaptive control, error compensation and multi-process manufacture (e.g. combined mill/turn/laser and grinding machines). These capabilities have made the programming task increasingly more difficult, making offline software tools for CAD/CAM a necessity for efficient generation and verification of NC code. Though the machine tools have changed radically, the programming language has basically remained the same with G & M code programming (ISO 6983-1 1982), which is based on the tool path and machine status description. In addition, the vendors and users have been seeking a common language for CAD, CAPP, CAM, and CNC, which integrates and translates the knowledge of each stage. Though there are many CAM tools to support NC manufacture, the problem of portability and interoperability from system to system has been and is still one of the key issues in limiting the wider use of these tools. Many solutions were proposed in the direction of a standard way of data exchange such as SET, VDA, and IGES, which were partially successful (Kemmerer 1999) but were not totally suitable to all the needs of the CAD/CAPP/CAM industry.

Since the mid-1980s, the international community has been developing the ISO 10303 set of standards, well known as STEP (ISO 10303-1 1994), which has its foundations in many of the earlier aforementioned standards. The STEP standard is divided into many parts, i.e. Description Methods, Information Models, Application Protocol (AP)s, Implementation Methods, and Conformance Tools. The Information Models and Application Protocols describe the data structures and constraints of a complete product model. Some of the most relevant APs used in the CAD/CAM domain include, Part 203: Configuration controlled 3D designs of mechanical parts and assemblies (ISO 10303-203 1994), Part 214: Application protocol: Core data for automotive mechanical design processes (ISO 10303-214 1994) and Part 224: Application protocol: Mechanical product definition for process plans using machining features (ISO 10303-224 2001). The Implementation Methods are protocols that are driven by the EXPRESS language (ISO 10303-11 1994)—the fundamental description tool of STEP. The first and perhaps the most popular implementation method is the STEP physical exchange file, often referred to as Part 21 file format (ISO 10303-21 1994). The Part 21 specification describes how EXPRESS-defined data are to be written in files in a standard way. The Standard Data Access Interface (SDAI) (ISO 10303-22 1998) is another implementation method that software developers can use to manipulate data defined by EXPRESS in the form of programming language bindings for C, C++ and Fortran. Recently, there has been a move towards using XML to represent and work with STEP data (Lubell and Frechette 2002, Hardwick 2004).

The STEP standard categorizes the various types of product data around APs. An AP includes at least three formal documents: (1) the Application Activity Model (AAM) describes the activities in the lifecycle of a product; (2) the pieces of product information that are needed for the activities are called the Application Reference Model (ARM); and (3) the Application Interpreted Model (AIM) is formed by using an EXPRESS information model to capture everything in the ARM and to tie it to a library of pre-existing definitions.

Today, a new ISO standard often known as STEP-NC is being developed to provide a data model for a new breed of intelligent CNC Controllers. Its ARM

has been given the number ISO 14649 (ISO 14649-111 2001, ISO 14649-1 2003, ISO 14649-10 2003, ISO 14649-11 2003, ISO/DIS 14649-12 2003, ISO/DIS 14649-121 2003), which represents a common standard specifically aimed at NC programming, making the goal of a standardized CNC controller and NC-code-generation facility a reality. Coupled with the ARM is the STEP-NC AIM, ISO 10303 Part 238 (ISO/DIS 10303-238 2003). The STEP-NC ARM (ISO 14649) provides an object-oriented data model for CNCs with a detailed and structured data interface that incorporates feature-based programming where there is a range of information such as the features to be machined, tool types used, the operations (Workingsteps) to perform, and the process plan (Workplan). Though it is possible to closely define the machine tool trajectory using STEP-NC, the aim of the standard is to allow these decisions to be made by a STEP-NC-enabled controller. The aim is that STEP-NC part programs may be written once and used on many different types of machine tool controller providing the machine has the required process capabilities.

This paper identifies the major developments with the standard and its impact worldwide for manufacturing processes such as milling, turning and Electrical Discharge Machining (EDM). The paper provides both international reviews of academically related research together with industrially oriented applications. The final part of the paper discusses major issues related to the standard together with a vision for its further development and future use.

## **2. Major global endeavours in STEP-NC related research**

Global research in the areas of STEP-NC is highly visible. There are three types of projects, those carried out (1) on the international scale, (2) across a few countries in the same region and (3) within a country/organization. This section presents a brief summary of these projects but leaves the technical details to be discussed in section 4. Interested readers may also refer to several references (Zhang *et al.* 1999, OMAC STEP-NC Working Group 2002, Xu and He 2003, Liu *et al.* 2004) for further information.

### **2.1 IMS STEP-NC project**

The IMS (Intelligent Manufacturing System) STEP-NC project (Maederl *et al.* 2002, IMS STEP-NC Consortium 2003), endorsed in November 2001, entails a true international package of actions with research partners from four different regions: European Union, Korea, Switzerland and USA. Table 1 shows the participants and the distribution of the technological scope within each region. The participants include end-users, academic institutions, and manufacturers of CAM systems, controls and machine tools. The regional coordinators are Siemens (EU), CADCAMation (Switzerland), STEP Tools (USA) and ERC-ACI (Korea). Siemens was also the inter-regional coordinator.

Formation of this IMS STEP-NC project is seen as the culmination of a number of regional projects carried out by different project groups/consortiums in the past 10 years or so, in particular the European ESPRIT STEP-NC Project, the Super Model Project, the STEP Manufacturing Suite (SMS) Project, and the Rapid Acquisition of Manufactured Parts (RAMP) Project.

Table 1. IMS STEP-NC Project partners (Xu and He 2003).

Region	EU	Switzerland	Korea	USA
Technologies covered	Milling, Turning, Wood/glass cutting, Stone machining, Inspection	Wire/Sink EDM	Milling, 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>	IRB, including <ul style="list-style-type: none"> <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> <li>● Louisiana Center for Manufacturing Sciences</li> <li>● Lawrence Livermore National Laboratories</li> </ul>
Research institute	<ul style="list-style-type: none"> <li>● WZL (RWTH AACHEN)</li> <li>● ISW (University of Stuttgart)</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>	
Association	<ul style="list-style-type: none"> <li>● KTH</li> <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>

## 2.2 European ESPRIT STEP-NC project

The European ESPRIT STEP-NC project started on 1 January 1999 and ended on 31 December 2001, although a substantial amount of pioneering research commenced as early as the mid-1990s when the European ESPRIT III project, OPTIMAL (Optimized Preparation of Manufacturing Information with Multi-Level CAM-CNC Coupling), was run from 1994 to 1997. Twenty industrial and academic partners with rich experience in the fields of CAD/CAM (Dassault, Open Mind), control (Siemens, OSAI), machine tools (CMS) and end-users (Daimler-Chrysler, Volvo) in Europe formed the European STEP-NC consortium.

The prototype for milling was demonstrated by the consortium in October 2001 in Aachen, Germany. This prototype was based on commercial systems from Siemens, Open Mind and Dassault Systems. The CAM modules from Open Mind (HyperFact) and Dassault System (Catia V5) generated the STEP-NC programs including high-level CAD geometry data, operation data and sequencing information. This program file was then passed to the shop floor, where a Siemens Sinumeric 840D control using ShopMill, a Siemens' shop-floor-oriented NC programming tool, was adapted to process the programs.

Research work regarding STEP-NC EDM is based on an Agie Charmilles machine tool at CADCAMation that realized a STEP-NC driven scenario for wire EDM. OSAI and CMS collectively realized a CAM output for Contour Cutting and used the STEP-NC information on an OSAI-controlled machine tool for wood machining.

In 2002, the European STEP-NC project moved into its second phase. In addition to further enhancement on the systems planned and developed in the first stage, this phase focused on the feedback mechanisms of STEP-NC (Denkena *et al.* 2002). The aim was to assess if the machining is adequately and accurately executed on the shop floor. To do this, inspection data were gathered, and a data model for handling the inspection data within a STEP-NC program was defined. Also being investigated in parallel is a scenario for verifying the data model and evaluating its benefits.

## 2.3 Super Model project

The 'Super Model Project' is a name for the Model Driven Intelligent Control of Manufacturing project awarded in October 1999 to STEP Tools, Inc., working with a team of sub-contractors. It was a \$2.9 million project funded by the National Institute of Standards and Technology (NIST). The goal of this project is to build a database that contains all the information required to make a part. The Industrial Review Board (IRB) includes representatives from organizations such as Boeing, Lockheed Martin, General Electric, General Dynamics Land Systems (GDLS), General Motors, Daimler-Chrysler, Gibbs and Associates and the Department of Energy (Albert 2001, Hardwick 2001).

A key part of the approach to the super model database is the use of XML in its interfaces. In this STEP-NC model, XML provides a convenient means to link manufacturing strategy, tool-path generation and tool-selection information to geometry, features and machining steps in the database. Based on the technology

developed at Honeywell Federal Manufacturing & Technologies (FM&T), a STEP-NC-enabled CAPP tool called ST-Plan was developed. This CAPP system creates machine-independent CNC control files from STEP (AP-203 or AP-214) data. Parameters such as tolerances, features, processes and tool requirements can be manipulated. ST-Plan claims to be the first-to-the-market software package dedicated to STEP-NC and e-Manufacturing. An open-source code library for STEP-NC called STIX has also been developed. The aim of this library is to combine the advantages of the AIM version of the STEP-NC with those of the ARM version.

#### ***2.4 STEP Manufacturing Suite (SMS) project***

SCRA (South Carolina Research Authority), under the sponsorship of the National Automotive Center, US Army Tank-Automotive and Armaments Command (TACOM), coordinated the SMS project that defines the Suite of STEP Application Protocols and the implementation architecture for STEP-enabled parts production within commercial and defence applications (SCRA 2004). These concepts were derived from the input of many countries and companies that participate in the ISO TC 184 SC 4 Working Groups as part of the STEP community. These countries include Canada, Germany, Sweden, Japan, UK and USA. Companies are led by Boeing, General Dynamics Land Systems, LSC Ltd, SCRA and STEP Tools Inc.

#### ***2.5 Rapid Acquisition of Manufactured Parts (RAMP) project***

The RAMP project has been in existence since 1986, addressing standards-driven applications for the manufacture of mechanical and electrical parts and assemblies. The major achievement of this project was the development and implementation of STEP standard AP224 as a part of the RAMP Program. This programme was initially funded by the Naval Supply Systems Command and later by the Defense Logistics Agency (DLA). TACOM NAC is the current sponsor of the technology under DLA's Strategic Sourcing Technologies contract. The UK RAMP Programme is an implementation of the RAMP technology in the United Kingdom, funded by the UK Ministry of Defence. This programme has been in place since 1998 and is in use in industry (Anonymous 2002).

#### ***2.6 Intelligent manufacture for STEP-NC-compliant machining and inspection***

This UK nationally funded project by the Engineering & Physical Sciences Research Council (EPSRC) started in May 2004, and is led by the AMST Centre at Loughborough University. The work aims to extend the EU research work using the Siemens 840D CNC for in-process measurement at the CNC machine and also explore the application and integration of the STEP-compliant NC standards between the CNC machine and a Coordinate Measuring Machine (CMM). A further major underlying theme of the research is the application of artificial intelligence to the CAPP/CAM/CNC process with the application of

agent technology through the use of data mining. The project is supported by a number of industrial partners, namely Renishaw, Siemens, LSC Group, Delcam and Rolls-Royce.

### 3. Overview of research activities

The crux of integrating design with manufacturing via STEP-NC is twofold, namely: product-data interchangeability and seamless product-information flow. STEP-NC is used as the ‘common language’ for NC manufacturing, as is STEP for the design processes; both formats are synchronized.

The first move toward ‘common language’-based product development has been to work with design models in the STEP (AP 203) format. A product model defined in terms of pure STEP geometry is re-interpreted in terms of the manufacturing features stipulated by STEP AP224. Process planning is then, or preferably at the same time, carried out. The outcome of this process planning can take two forms, an ISO 10303 AP238 (ISO/DIS 10303-238 2003) file, i.e. a STEP-NC AIM file, or an ISO 14649 (ISO 14649-111 2001, ISO 14649-1 2003, ISO 14649-10 2003, ISO 14649-11 2003, ISO/DIS 14649-12 2003, ISO/DIS 14649-121 2003) file, i.e. a STEP-NC ARM file. This file includes the information about the design model itself, the stock, its manufacturing features, the tool/fixture requirements and the manufacturing process sequence, and allows complete safety checking, which can be carried out on the shop floor before the data are processed at a machine tool. The information in this file can then be used as input to a STEP-NC-enabled CNC controller that understands the information such as Workplans and Workingsteps present in the file and drives the machine tool.

The above-mentioned, unified design and manufacturing scenario can be described using figure 1. Note that the product information flow is accompanied by different ‘derivatives’ of STEP standards at different stages. Hence, both product data interchangeability and seamless product information flow are enabled. Accordingly, the current research activities can also be grouped to the different stages as shown in figure 1. The following sections review the research

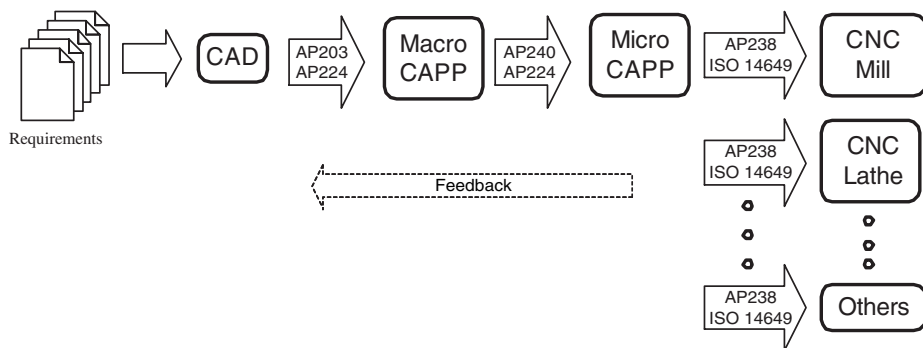


Figure 1. Integrating design with manufacturing via STEP/STEP-NC.

work carried out in Korea, the European Union, UK, USA and New Zealand. The research work presented in each section is sequenced as described above, i.e. CAD-CAPP-(CAM-)CNC.

#### 4. STEP-NC-related research

Substantial research work has been carried out by research groups from countries such as Germany, Switzerland, UK, Korea, USA and New Zealand. Some of the projects have been coordinated across a few countries, and some have not. The following sub-sections summarize the research work by these countries.

##### 4.1 Research work in Germany

The research focus in Germany is on the development and implementation of STEP-compliant CAPP/CAM systems and NC controllers. Two German institutes—ISW in Stuttgart and WZL RWTH in Aachen, and a CNC system vendor, Siemens—have been the main players in the European STEP-NC project. A prototype system named *STEPturn* has been developed at ISW (Storr and Heusinger 2002). This adopts STEP and STEP-NC standards for turned parts. Generally speaking, *STEPturn* is a CAPP system bridging CAD and CAM. *STEPturn* first reads geometry data from a STEP AP-203 Part 21 file and then performs normal process-planning tasks such as feature recognition and Workingstep sequencing in order to generate a STEP-NC physical file.

Also developed at ISW is a Workingstep planning methodology to support automatic Workingstep optimization for turned parts (Storr *et al.* 2002). The Workingstep optimization is based on the features and machining operations in STEP-NC as the basic elements. At the beginning, manufacturing priorities are assigned to different features as shown in figure 2 (Storr *et al.* 2002). Two different kinds of manufacturing priorities are defined. 0/1 (or 1/0) means a firm machining sequence where feature 1 (and its corresponding Workingsteps) has priority over feature 0 (and its corresponding Workingsteps), or vice versa. When such a manufacturing sequence exists, Workingsteps must be executed in the expressed sequence. A + (or +/+) symbol means that the manufacturing priorities are still pending, or the manufacturing priorities are on par. Additional information, such as geometric and machining parameters, is required to determine the final sequence(s). The table to the left of figure 2 should be prepared and read in a specific manner. For example, to obtain a priority sequence for the 'Outer\_diameter' and 'Cut\_in' features, a parallelogram as shaded in the table is first identified. Then, the numbers/symbols in the parallelogram are extracted, e.g. 1/0 in this case. The relationship between Outer\_diameter and Cut\_in can therefore read '1/0', meaning Cut\_in can only be machined after Outer\_diameter. After the manufacturing priorities are decided, Workplans can be generated. Features are grouped in pairs and ordered according to the priorities to obtain a rough Workplan. The final Workplan and STEP-NC program are built based on the rough Workplan, geometrical information and manufacturing parameters. Figure 3 illustrates the steps of sequencing the Workingsteps (Storr *et al.* 2002).



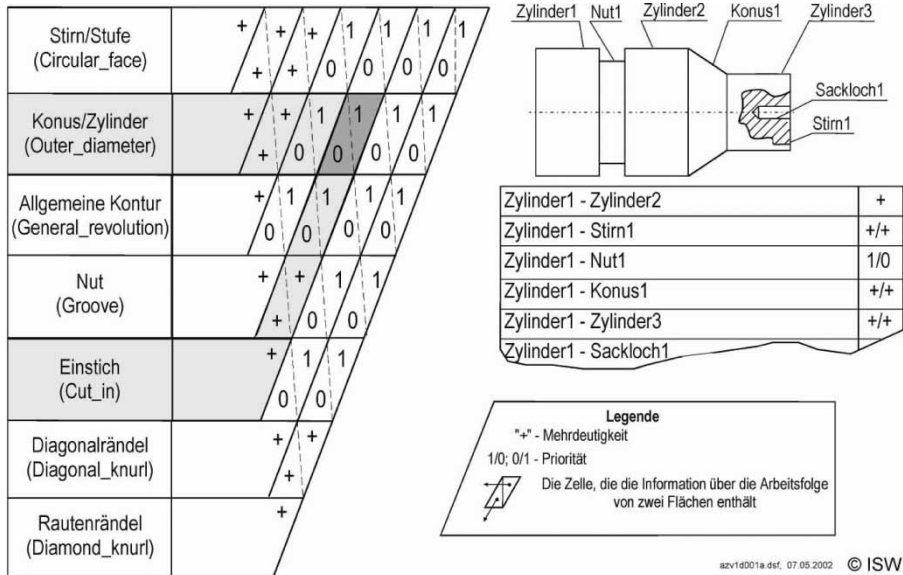


Figure 2. Manufacturing priorities (Storr et al. 2002).



Figure 3. Workingstep sequencing (Storr et al. 2002).

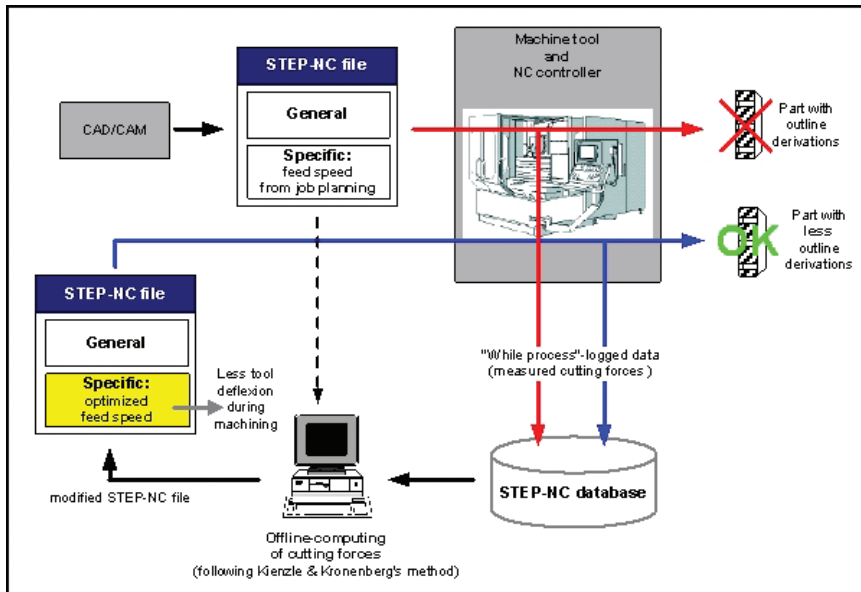


Figure 4. Feedback information for STEP-NC (Denkena *et al.* 2002).

Another piece of research carried out at ISW aimed to pass the feedback from a CNC controller to a CAM system using STEP-NC (ISO 14649) (Denkena *et al.* 2002). This is done through logging cutting forces during the NC processes into a database so-called STEP-NC as per figure 4. By investigating the logged data, compensation algorithms and models for tool deflection in high-speed machining, for example, are used to modify the NC program in an offline computing process (figure 4) (Denkena *et al.* 2002).

The Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University focuses on STEP-compliant CAM and NC controllers. It has developed the first industrial prototype of a STEP-compliant NC controller based on the Siemens 840D controller (Weck *et al.* 2001, Wolf 2001, Weck and Wolf 2002). A graphical user interface has been developed, using Shop Mill (a shop-floor-oriented NC programming tool) and Sinumerik 840D HMI (Human–Machine Interface). This interface can parse STEP-NC program files (figure 5) (Weck and Wolf 2002).

The Workingsteps are executed based on the existing NC-cycles, or directly compiled to yield switching commands and processed to control specific geometrical interpolation formats. Figure 6 illustrates the architecture of the STEP-NC-enabled Siemens controller (Weck and Wolf 2002).

#### 4.2 Research work in Switzerland

A number of system vendors and institutes in Switzerland have taken part in the STEP-NC project: Starrag, AGIE, AMT, CADCAMation, EIG i-tech, Derendinger, EPFL and Wyss. The work focuses on STEP-NC Part 13—Process data for wire

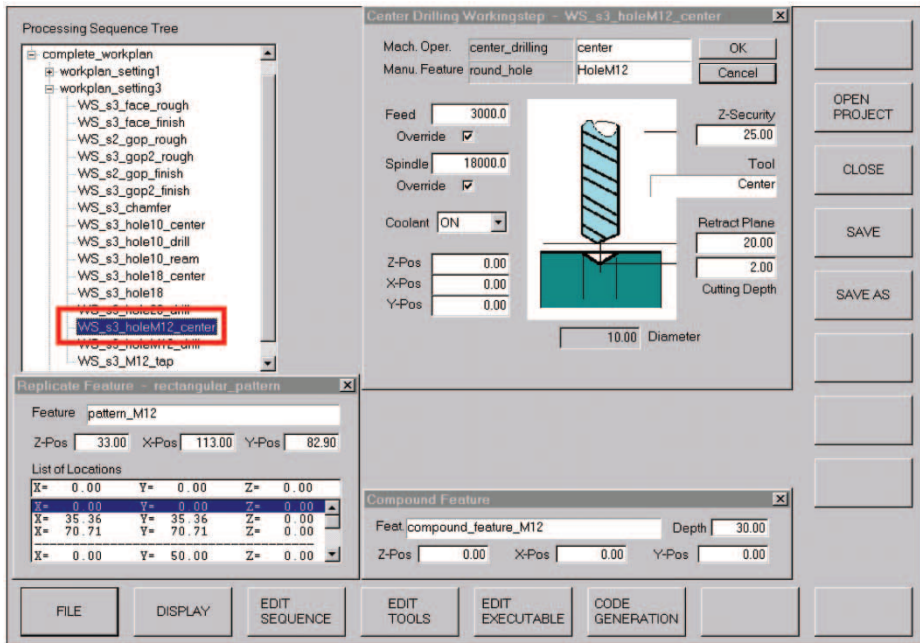


Figure 5. Graphical user interface for STEP-NC (Weck and Wolf 2002).

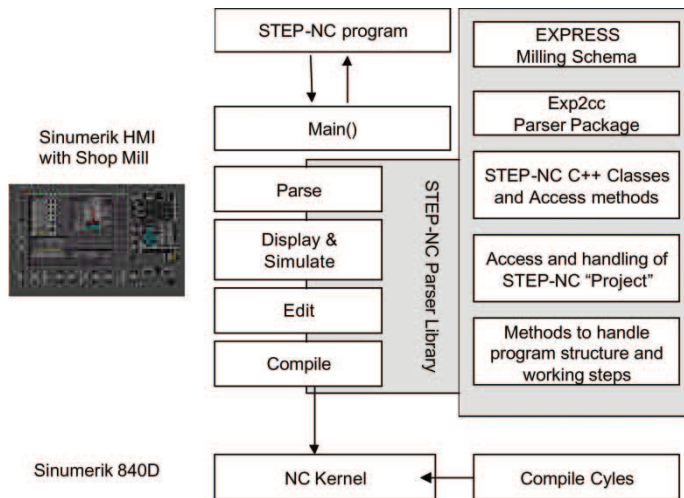


Figure 6. STEP-NC enabled Siemens controller (Weck and Wolf 2002).

EDM and STEP-Compliant CNC controllers for wire EDM. The data model for wire EDM has been constructed (figure 7) (Anonymous 2003a, Erdős and Xirouchakis 2003). A prototype STEP-compliant wire EDM system using Agie-Charmilles controllers has also been developed (figure 8) (Richard and Stark 2002). In the prototype system, SolidWorks was used as the design tool to construct solid models. An additional model, which provides STEP-NC supports, was

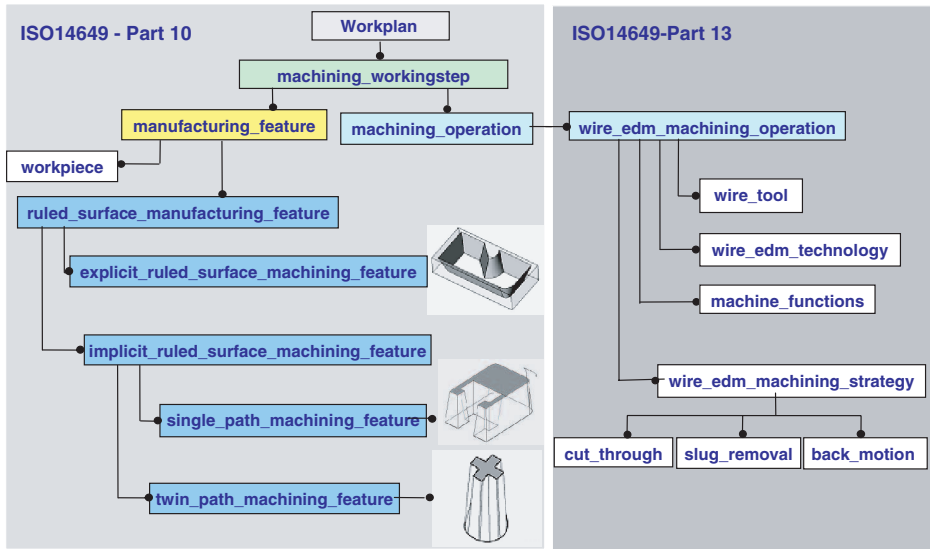


Figure 7. Data model for Wire EDM (Anonymous 2003a, Erdős and Xirouchakis 2003).

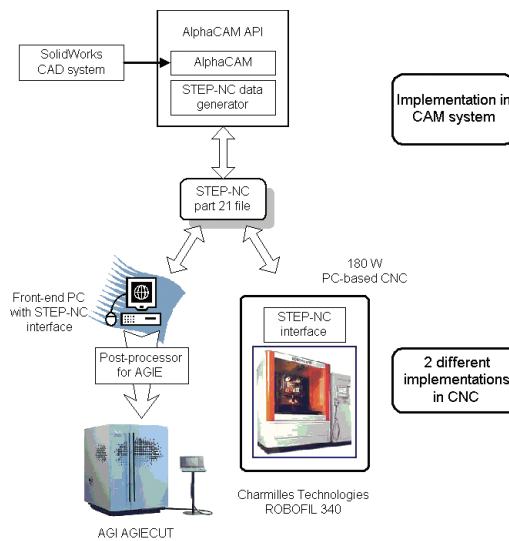


Figure 8. Prototype wire EDM system developed in Switzerland.

constructed in the AlphaCAM system. The design data are then translated into ISO 14649 files through AlphaCAM and a STEP-NC data generator. Two different systems have been implemented on the shop floor. In the first system, STEP-NC data were translated into a native CNC program for AGIE AGIECUT, a traditional CNC controller through a front-end PC which has a STEP-NC interface and a post-processor implemented. In the second system, the ROBOFIL 340 from Charmilles implemented a STEP-NC interface within the controller so that it can directly accept STEP-NC programs.

### 4.3 Research work in the UK

Two STEP- and STEP-NC-related projects in the UK deserve mentioning; both projects are independent from the European collaborative STEP-NC project and the IMS STEP-NC project. The first project is the Agent-Based CAM (AB-CAM) system developed at the AMST Centre in the Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University. The second project is the RAMP (Rapid Acquisition of Manufactured Parts) project developed and implemented by the LSC Group in UK.

The Loughborough project adopts STEP data models to construct an Agent-Based CAM system as shown in figure 9. Three frameworks have been proposed for implementing STEP data models in the system (Rosso *et al.* 2002, Allen *et al.* 2003, 2004, Newman *et al.* 2003):

1. a system that can import and export STEP-compliant NC data;
2. a system with a STEP-compliant NC data support structure; and
3. a system with a kernel STEP-compliant NC data structure.

The AB-CAM system was developed based on the second framework. It uses STEP external data for interpreting the native CAD/CAM geometric and manufacturing routines. The functionalities of the AB-CAM system cover feature extraction, generation of STEP-compliant process plans and generation of controller-specific part programs. It has been proposed that an AP-224 translator could be developed

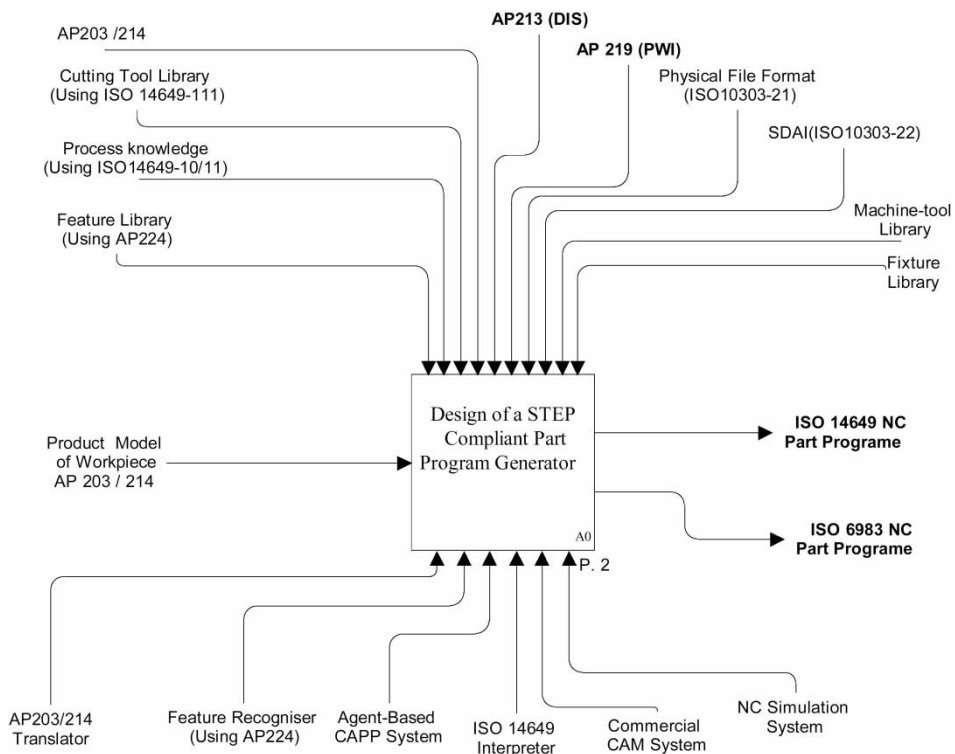


Figure 9. Structure of the AB-CAM system (Newman *et al.* 2003).

to capture the feature information from a feature-based CAD model (Rosso *et al.* 2002, Allen *et al.* 2003, 2004, Newman *et al.* 2003). If the feature information is not available, an automatic feature-recognition system will be used. The STEP-compliant process plan generator selects a process type, machine tool, cutting tool, cutting parameters, fixture methods and clamping locations to transfer a feature into a Workingstep in the STEP-NC file. It bridges CAD and CAM systems via a set of process-planning activities. The AB-CAM system does not have an intermediate stage. The output from the AB-CAM system is native STEP-NC files. The initial agent-based work has formed the basis of the new EPSRC research programme at Loughborough outlined earlier.

In the RAMP project, the original designs are translated into STEP AP-224 files using a software tool named STEPTrans to remove any reliance upon turnkey or proprietary products. Figure 10 illustrates the manufacturing data flow in the RAMP project (Anonymous 2002). LOCAM is a CAPP system developed by the LSC Group in the UK.

The STEP AP-224 files constitute a so-called 'neutral' form of the information required for machining (i.e. milling and turning) process planning and are not tailored to the requirements of any particular process-planning system or predetermined manufacturing process (or route). A knowledge base of manufacturing rules and constraints is then input to the planning system, which makes the activity conformant to a specific manufacturing environment and company practices. The process planner can then plan from any AP-224 file, regardless of the design system that was used to generate the data. The designing data are kept generic until a certain CAM system uses that AP-224 file for planning and generating specific NC programs.

According to the tests conducted in a UK Navy pilot project, RAMP processing was found to be an average of 3.5 times faster than using conventional methods

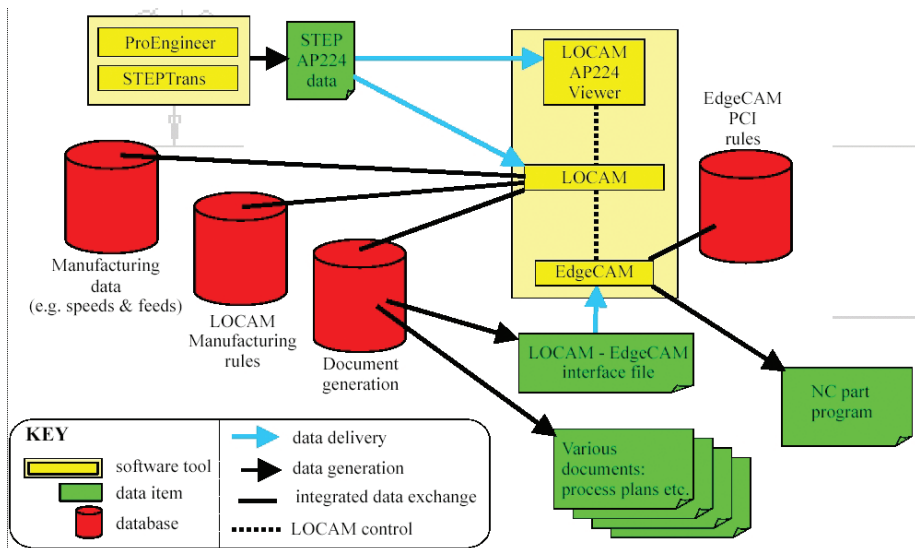


Figure 10. Manufacturing data flow in RAMP (Anonymous 2002).

for new orders. In a fully integrated RAMP production, the predicted improvements factor rises to 14, while for repeat orders, RAMP processing was found to be an average of 1.5 times faster than using conventional methods; and in a fully integrated RAMP production, the predicted improvements factor rises to 9 (Anonymous 2002). STEP-NC is currently being implemented in the RAMP project. This effort is believed to be less arduous, as feature definitions in STEP-NC are primarily the same as those defined in STEP AP-224.

#### 4.4 Research work in Korea

In Korea, there are two groups of researchers actively working in the area: NRL-SNT (National Research Laboratory for STEP-NC Technology) in Pohang University of Science & Technology (Suh and Cheon 2002, Suh *et al.* 2002a, b, 2003) and ERC-ACI (Engineering Research Center for Advance Control and Instrumentation) in Seoul National University (Lee and Bang 2003a, b).

In 1997, NRL-SNT started working on a Feature-Based (STEP-NC) control system. To date, they have:

1. developed a STEP-based autonomous NC system;
2. built an open architectural virtual manufacturing system; and
3. standardized STEP-NC technology for the Korean environment.

The ERC-ACI group at the Seoul National University is mainly working toward developing an XML-enabled STEP-NC data model for milling. This includes:

1. extensions of the interface to include other technologies (Lee and Bang 2003a);
2. rebuilding XML files to reflect changes made to the user-specific data (Lee and Bang 2003b); and
3. searching for, extracting and storing the tool-path generated in XML format.

The newly developed CNC controller is called the Korean STEP-NC system (Suh *et al.* 2002b). Its key component is a computer-assisted part programming system—Shop-Floor Programming (SFP) system. Its primary function is to generate part programs in ISO 14649 (or STEP AP238) format to machine the part defined by a STEP AP203 or AP224 file (Suh *et al.* 2003). The SFP system covers the entire spectrum of STEP-NC-related research as shown in figure 1. Discussions in the following sections are therefore arranged in accordance with the sequence present in figure 11.

#### 4.5 Korean STEP-NC system in NRL-SNT

**4.5.1 From CAD to STEP-NC.** Going from CAD to STEP-NC, the SFP system can generate STEP-NC ARM programs based on initial CAD files (STEP AP203 physical files). It can also take an existing ARM file to generate another version of it according to the NC facilities that were not considered in the previous version. Figure 11 describes the functional architecture of the SFP system which consists of (1) STEP AP203 and ISO 14649 physical file interpretation, (2) feature recognition, (3) process planning, (4) part program generation and (5) verification (Suh *et al.* 2003, Suh and Cheon 2003).

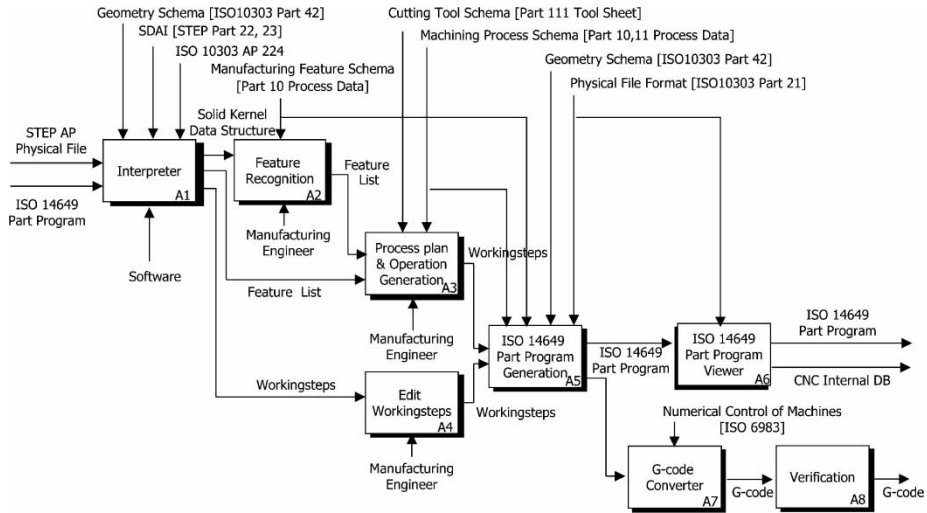


Figure 11. IDEF0 diagram for SFP system (Suh and Cheon 2002).

The Interpreter (A1) can take a STEP AP203 physical file as input from a CAD system. Through feature recognition, an initial feature list is generated following the manufacturing feature schema (STEP AP224). These features are then input to the process planning stage, during which time the native machine tool information and machining parameters are added to the program. Workingsteps of each manufacturing feature are defined and saved into an ISO 14649 part program.

Alternatively, an ISO 14649 part program can be directly used as an input. Through the Interpreter, the existing STEP-NC program is decomposed into a feature list and Workingsteps. Then, the native information stored in a database is mapped to the original (generic) STEP-NC program. As a result, a generic STEP-NC program is converted to a native program.

SFP has an interface for Input Manager and Process Planner (Suh *et al.* 2003). The roles of the Input Manager are to interface with CAD data (STEP AP203) and recognize manufacturing features. The output is stored in the Manufacturing Feature Database. The Process Planner determines the processing sequence, operations, fixtures, set-ups and cutting tools required to machine the features. It also optimizes these native parameters based on the Machining Knowledge to arrive at a native STEP-NC program.

**4.5.2 From CAM to native CNC process plan.** The information in an ISO 14649 part program is converted into the internal data format, i.e. a process sequence in the form of ‘process sequence graphs’ (figure 12) (Suh *et al.* 2002a).

The EXPRESS compiler in the Interpreter converts the physical file, in the form of ‘task description’ into a Process Sequence Graph (PSG), based on the information such as geometry, technology and tool description. PSG represents the sequence of Workingsteps described in terms of machining\_feature and machining\_operation using the ‘AND–OR’ relationship (figure 13) (Suh and Cheon 2002, Suh *et al.* 2003).

Given the manufacturing features, machining operations (figure 13(a)), and their PSG (figure 13(b)), the part can be machined in a number of different ways,



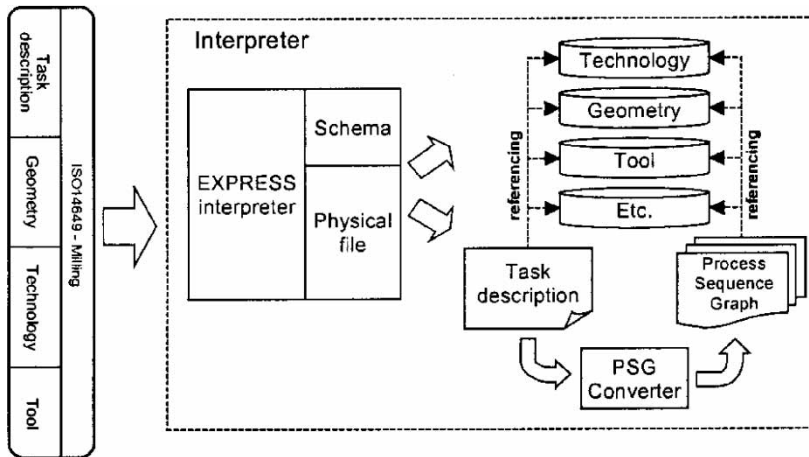


Figure 12. Interpreter function (Suh *et al.* 2002a).

e.g. 1-8-2-7-3-4, 1-3-4-2-6-5-7 or 1-3-4-2-5-6-7. Hence, CNC execution can be made flexible, optimal, intelligent and autonomous (Suh *et al.* 2002a).

In preparation for executing a STEP-NC program, two different approaches have been used, a STEP-NC-enabled CNC controller and a conventional CNC controller. The former includes a Tool Path Generator (PosTPG), a Tool Path Simulator (PosTPS) and a soft-CNC called NCK/PLC (Suh *et al.* 2002b). The Tool Path Generator generates the tool path for each Workingstep in four segments: approach, machining, retract and departure. The generated tool path can be graphically visualized by the Tool Path Simulator, and the verification data can be stored in the Tool Path Database. NCK/PLC has been developed and used to convert the STEP-NC data model into machine tool motion. NCK/PLC is capable of NURBS interpolation, look-ahead control, position/velocity interpolation and PID control. It interfaces with machine tool hardware (drivers and motors) via an I/O board. A suite of NCK/PLC algorithms has also been developed.

If a conventional CNC (only accepting ISO 6983 code) has to be used, conversion from ISO 14649 to ISO 6983 is performed as shown in figure 11 (Suh *et al.* 2002a). This requires explicit tool path computation in which the cutting tools to be used should be the same as those specified in the ISO 14649 part program. In other words, the required cutting tools should be available in the tool magazine of the local CNC machine. The computed tool path can also be verified (figure 11).

**4.5.3 Execution of a process plan on a CNC machine.** The generated tool paths are stored in the Tool Path database in terms of unit features. When execution commences, the executor pulls a unit tool path from the Tool Path database and then converts it into NC codes (figure 14). These converted NC codes are stored in an NC-code database. At the end, the NC code is pulled by NCK and executed, driving the hardware units such as spindle, machine table, tool magazine, ATC, APC and coolant (Suh *et al.* 2002a). When traversing of the current NC-code reaches the end, the next tool path (of a unit feature) is pulled out from

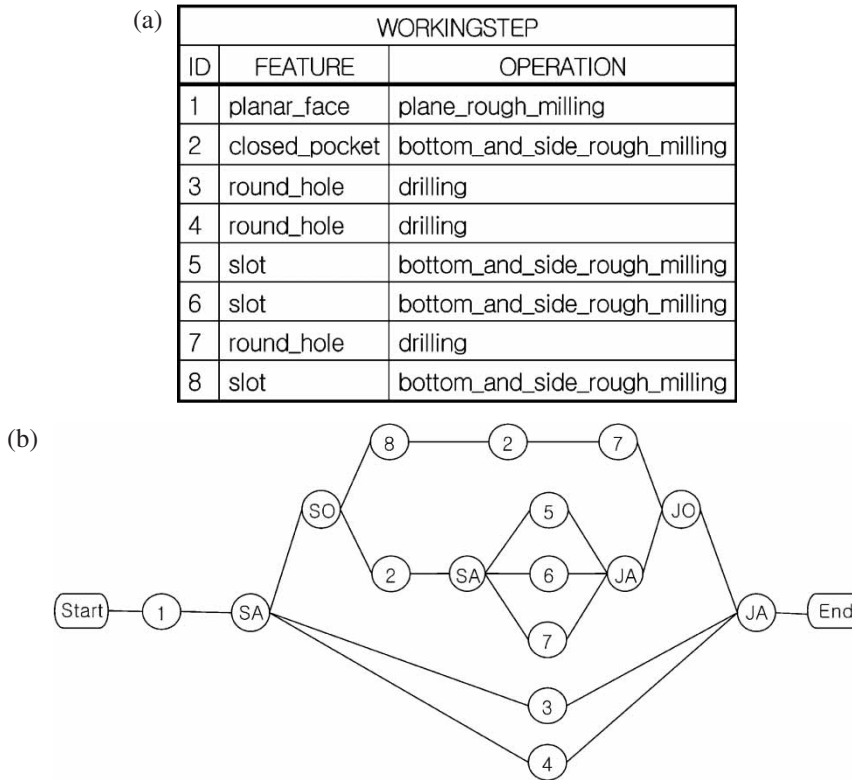


Figure 13. (a) Workingstep list. (b) Process sequence graph.

the Tool Path database. This continues until all the tool paths are pulled out. Then, the Executor reports to Scheduler that the current Workingstep has been successfully completed.

**4.5.4 XML-based STEP-NC.** ERC-ACI at the Seoul National University have developed an XML-based STEP-NC system (Lee and Bang 2003a). An XML-based STEP-NC system has a number of merits:

1. Existing software tools as well as previous research results can be utilized. This reduces the time and cost of program development.
2. The XML processing ability supports an e-manufacturing scenario.
3. As an XML file can be used as a data structure, there is no need to make the internal data structure for data interpretation.
4. Machine tools can share information with other departments in and outside the company.

The milling machine used to test the system contains four modules, as illustrated in figure 15: XML Data Input module, Interpreter, Tool Path Generator and Motion Control Board. The XML data Input Module and Interpreter generate STEP-NC programs from CAD files, whereas the other two modules generate native CNC process plans and execute STEP-NC programs.

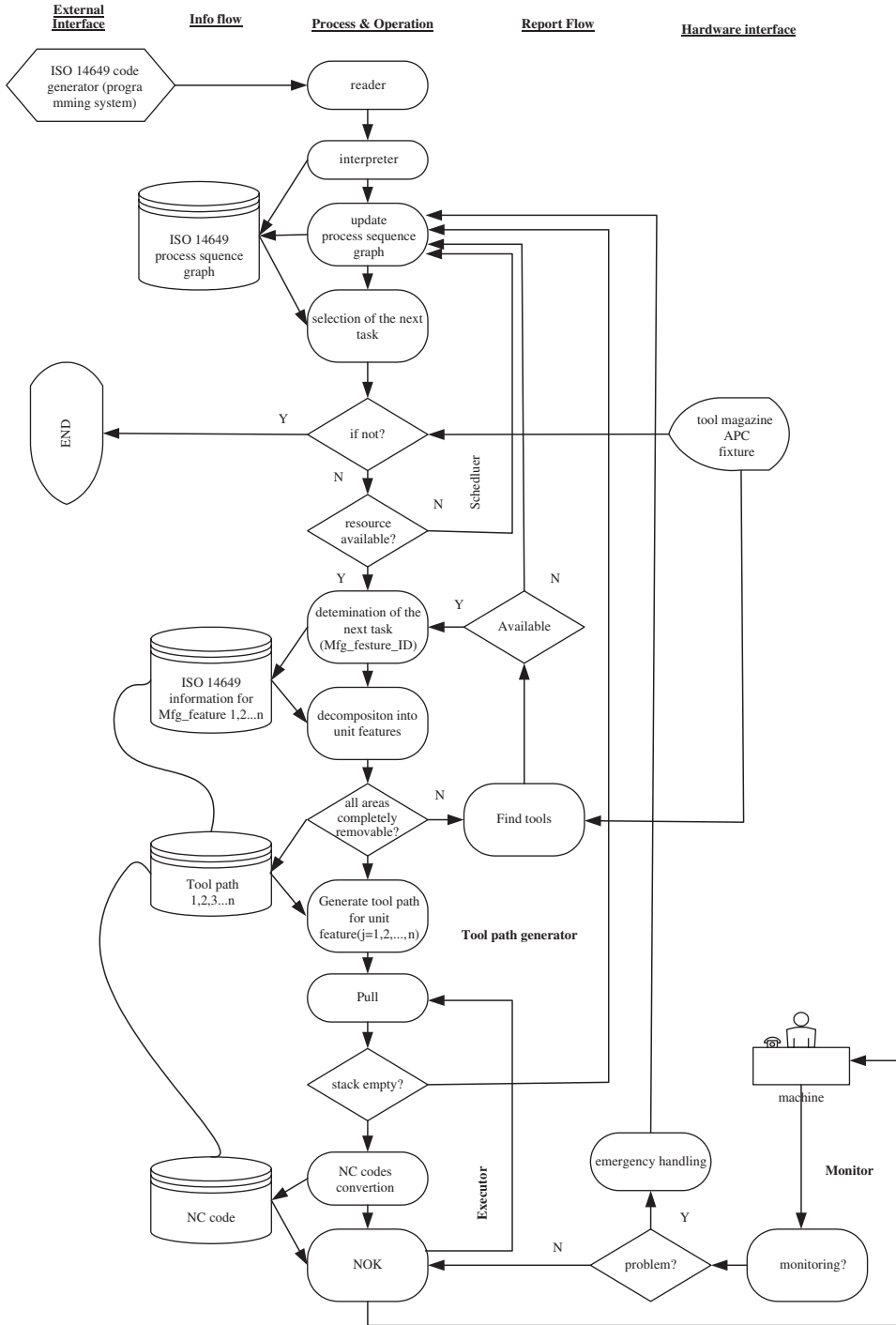


Figure 14. Operational flow of a STEP-compliant CNC (Suh et al. 2002a).

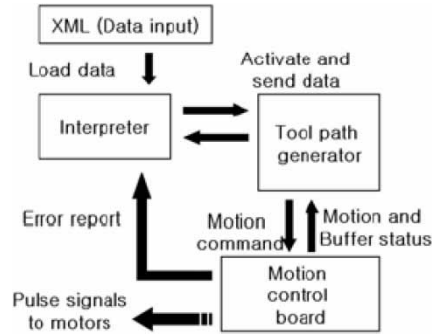


Figure 15. STEP-NC milling machine (Lee and Bang 2003a).

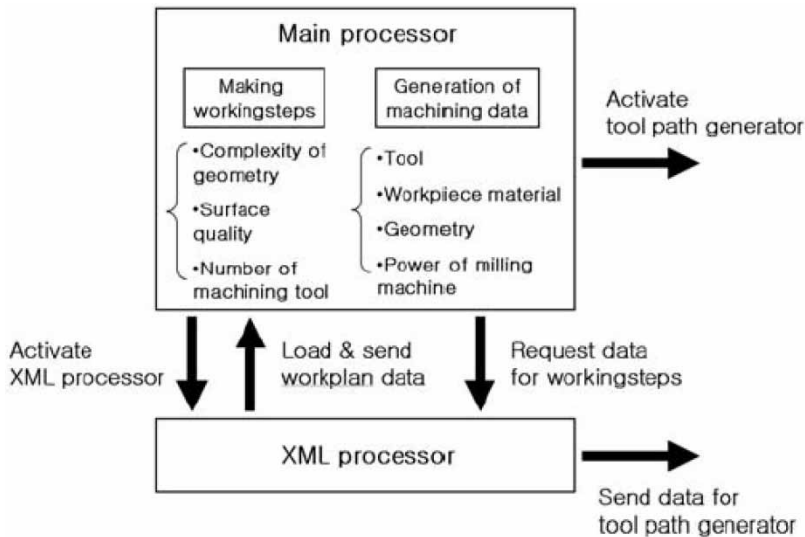


Figure 16. Interpreter module (Lee and Bang 2003a).

**4.5.5 From CAD to STEP-NC.** In the XML Data Input module, an XML STEP-NC file was created by adding definitions of entities and attributes of STEP-NC. The tag name of an entity was defined to indicate the attribute name of its higher entity. This ISO14649 is then interpreted by the Interpreter (see figure 16) to obtain the manufacturing features in XML format. At the same time, the Workingsteps are determined by geometric characters, surface quality and machine tools. Once Workingsteps have been established, the operations for each Workingstep are defined based on the machine status, workpiece material and machining tool data stored in the STEP-NC file. When the machining environment changes, the information about machining status, tools or materials is sent to the Interpreter. The Interpreter generates a new set of machining data, and the Tool Path Generator generates new tool paths accordingly.

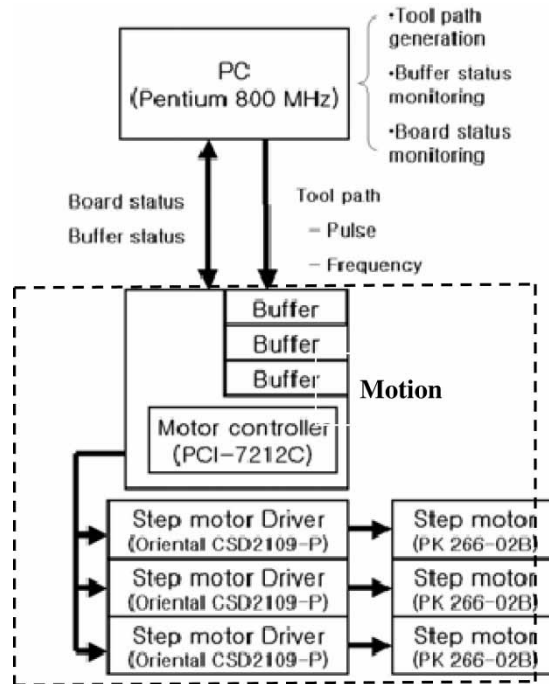


Figure 17. PC and a motion control board.

**4.5.6 Execution of a process plan on a CNC machine.** A STEP-NC process plan is executed through a PC and a motion control board (figure 17) (Lee and Bang 2003a). According to the workpiece geometry (boundary and cutting depth) and setup information (location and position), the PC performs calculations and generates tool paths with native machining parameters, such as rotational speed of spindle, feed rate, feed direction, step over direction, offset amount, overcut length and retract plane in the Tool Path Generator. The Tool Path Generator also decides if the machining is completed. If the machining is complete, the tool retreats to a retract plane. Otherwise, the tool performs an offset motion calculated by a step over direction and the offset amount. Once the tool paths are confirmed, these values are sent to a board, where one or more buffers of the motion control board may be empty. To enable simultaneous machining, calculations must be finished before all the buffers are vacated. To finally execute the NC program, the motion control board activates the motors of the machine by pulse signals commanded by the PC.

#### 4.6 Research work in the USA

**4.6.1 STEP-NC-related research in the Intelligent Systems Division at NIST.** The Vertical Workstation System (Kramer and Jun 1986), a feature-based system for piece-part machining, was developed at NIST in the 1980s. This was followed by an intensive investigation of machining feature issues (Kramer 1994) and the definition of a library of Material Removal Shape Element Volumes (MRSEVs)

(Kramer 1992) based on the features library originally developed by the STEP Form Features committee. An automated programming system using six types of input data in STEP Part 21 files (Kramer 1991) was developed in 1991 that was able to generate NC code for machining parts whose features were from a subset of the feature types in the MRSEV library.

Building on this earlier work, toward the end of 1990s, a Feature-Based Control System was developed (Kramer and Proctor 1996) in the NIST Intelligent Systems Division (ISD). This grew by the addition of inspection and a major restructuring into the Feature-Based Inspection and Control System (FBICS) (Kramer *et al.* 2001, 2004). FBICS is a hierarchical control system conforming to the Real Time Control System (RCS) architecture (Kramer *et al.* 1998, 2000, 2001, 2004). One of the main purposes of FBICS is to test the usability of STEP methods and models. FBICS and other ISD STEP-based systems described below rely heavily on the capabilities for handling EXPRESS schemas and STEP Part 21 files provided by ST-Developer from STEP Tools, Inc.

The two principal capabilities of FBICS are to generate process plans automatically at each level of a control hierarchy and to execute the plans in order to make and/or inspect piece parts. In FBICS, information models built in EXPRESS are used for all types of data (except machining and inspection programs) and data files are in STEP Part 21 format. This includes models of (1) cutting tool catalogue and inventory, (2) process plans, (3) shape of workpiece before machining, (4) intended shape of workpiece after machining, (5) fixture, (6) machining features, (7) setup data, (8) user preferences for system behaviour, (9) executable operations, and (10) rules for selecting feed, speed, stepover, pass depth, and coolant usage. Machining features, workpieces, and fixtures are represented using the STEP AP 224 ARM. An EXPRESS schema for ALPS (A Language for Process Specification; Catron and Ray 1991) is used for process planning. Ad hoc EXPRESS schemas are used for user preferences, set-up descriptions, shop and workstation operations, and tool usage rules.

FBICS exists both (1) as a stand-alone system using minimally functional controllers but fully functional planners, with simulated inspection or machining (figure 18), and (2) as part of three loosely integrated systems using the same planners but more fully functional controllers with graphically simulated inspection, actual inspection, and actual machining. Machine tools that have been run using FBICS include a three-axis 'mini-mill' machining centre, a Bridgeport three-axis machining centre, a hexapod machining centre and a Cordax coordinate measuring machine. To integrate FBICS with actual machines, it has been necessary only to replace the 'Task2' process of figure 18 with the control process of an actual machine and to make minor changes in the protocol for interprocess communication.

ISD research concerning STEP-NC technology and participation in STEP-NC standards development commenced in the late 1990s. An ISO 14649 (ARM) Interpreter has been developed. The interpreter reads a STEP Part 21 file based on the schemas in Parts 10 and 11 of ISO 14649 and generates canonical machining commands (described below). Execution of the first example (figure 19) in Annex F of Part 11 of ISO 14649 has been achieved with the ISO 14649 interpreter. Machining operations that the interpreter can handle include centre drilling, countersinking, counterboring, reaming, rough face milling, finish face milling, rough milling rectangular pockets, and finish milling rectangular pockets. ISD is

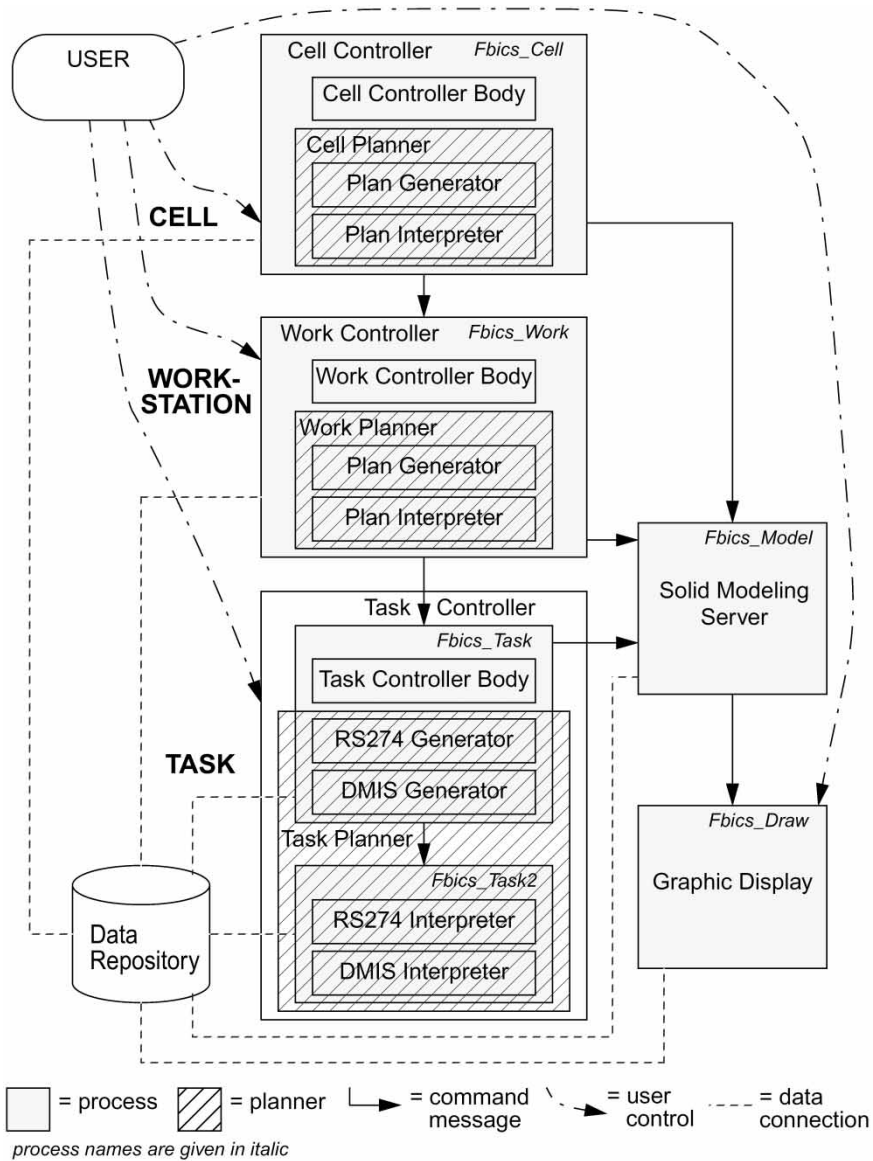


Figure 18. FBICS stand-alone architecture (Kramer *et al.* 2004).

now developing an AP238 (AIM) Interpreter. The initial target of the AP238 interpreter is to be able to execute the AP238 equivalent of the aforementioned example.

ISD has had an Enhanced Machine Controller (EMC) project, starting in the 1990s and continuing into the 2000s. The objective of the EMC project is to build a testbed for evaluating application programming interfaces (APIs) for open-architecture machine controllers. The EMC project has built its own machine tool controller, following the RCS architecture. The controller (Proctor *et al.* 1995) and its variants are called 'the EMC controllers'. EMC controllers have been installed on several machining centres in commercial machine shops. The EMC

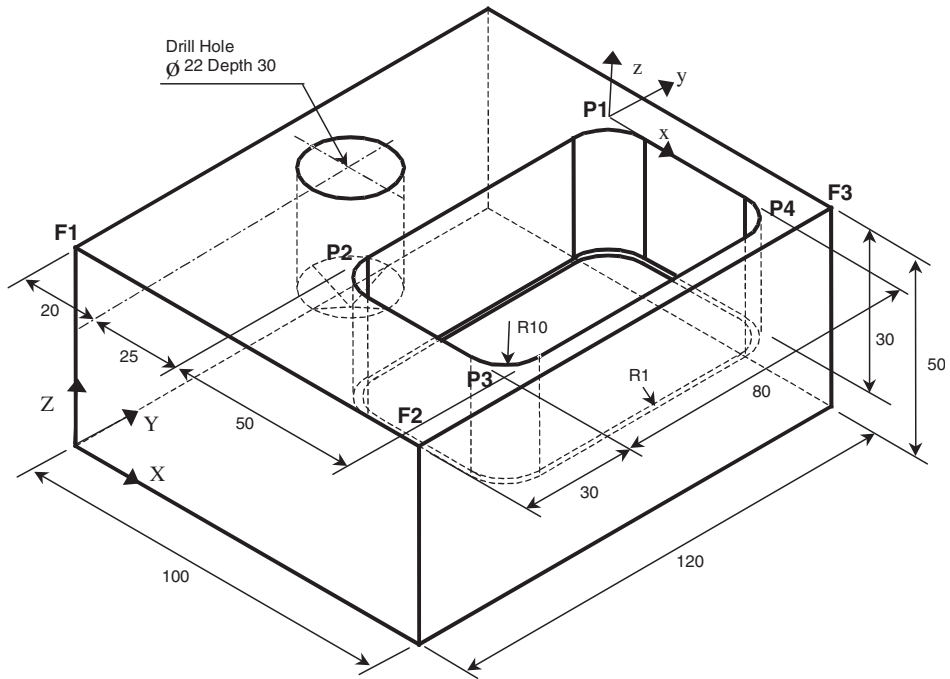


Figure 19. Workpiece of Example 1 in Part 11 of ISO 14649 (ISO 14649-11 2003).

controller incorporates either an NC-program interpreter (Kramer *et al.* 2000) for programs written in the RS274 language or the ISO 14649 interpreter for programs contained in ISO 14649 STEP Part 21 files. Of particular significance in the EMC system is a set of canonical machining commands (Proctor *et al.* 1996). The commands are used by the EMC controller at the interface between either program interpreter and lower-level controllers for I/O and trajectory control. They can be used to drive three-axis to six-axis machining centres. They have also been used in ISD to drive tool-path drawing systems for both RS274 and ISO 14649.

ISD has also built a translator that will read FBICS workstation-level data for machining a part—process plan, features, setup, and tooling (all in STEP Part 21 files)—and write an ISO 14649 STEP Part 21 file containing the same plan and other data. This has not yet been documented.

**4.6.2 Research work carried out at STEP Tools Inc.** ST-Plan is a STEP-compliant system to integrate CAD with CAPP. It creates machine-independent CNC control information via a ‘STEP in, STEP-NC out’ approach. ST-Plan has two major modules, FBMach (Feature-Based Machining) and FBTol (Feature-Based Tolerancing). FBMach is used to recognize manufacturing features and allow Workingsteps to be defined for those features, and FBTol is used to define tolerances.

FBMach has been developed by Honeywell Federal Manufacturing and Technologies (FM&T) (Brooks and Wolf 1994, Brooks and Greenway 1995, Albert 2001). It contains a library of machining features and feature-recognition algorithms. The system creates both surface and volume-based machining features.



A surface-based machining feature is based on sets of faces on the solid model—the ‘skin’ that represents the shape of a feature. A volumetric machining feature is represented by ‘delta volumes’, which are solid bodies showing the shape and amount of material to be removed. Tool paths may also be determined by delta volumes in applications for generating CNC routines.

FBMach uses three different approaches to define surface features: (1) automatic recognition, (2) interactive recognition and (3) manual identification (Brooks and Wolf 1994, Brooks and Greenway 1995, Han *et al.* 1998, 2000). The automatic recognition uses a procedural algorithm to search for feature hints and then creates feature instances using the hints without user interaction. The interactive recognition allows the user to provide some hints for FBMach to use in generating the feature instances. For example, the user may identify a pocket by selecting its bottom face. The manual identification allows the user to create a feature instance by adding each face to the feature individually and defining each face’s role in the feature (side, bottom, top, etc.). In STEP-NC terms, FBMach users can identify Workingsteps based on the machining features defined by AP 203/AP 224 format. These Workingsteps can then be arranged to form the appropriate sequence, creating a complete process plan, i.e. Workplan. The Workingstep and Workplan information is then saved in the STEP-NC (AP 238) file which may be passed on to a CAM system using ST-Machine (CAM plug-in suite for STEP-NC), for example.

A useful feature of FBMach is its ability to generate ‘in-process models’ that represent the shape of the workpiece before and/or after a machining operation. These models allow planners to see how a process plan or machining strategy progresses step by step until the final component is shaped. FBMach is limited to prismatic parts at the moment.

In order to process AP-238 (AIM) data for a CAM/CNC system, an Open Source Code Library called STIX has been developed. With STIX, the advantages of the STEP AIM (integration, upward compatibility) can be combined with those of the STEP-NC ARM (understandability). STIX is still under development with addition of more access functions (e.g. those for traversal of data, data browser and COM for milling applications) and data-creation functions (e.g. those for a subset of STEP-NC functionality and COM for milling applications) (IMS STEP-NC Consortium 2003).

At the CNC end, STEP Tools Inc. has developed a suite of CAM plug-ins called ST-Machine, i.e. Plug-in for GibbsCAM and Plug-in for MasterCAM. These plug-ins are effectively customized command parsers and command interpolators for processing STEP-NC, when keeping the I/O structure and servo system of the machine intact. They can read AP 238 files, build CAM geometry, match cutting tools, build CAM operations, optimize, verify and post the machine commands to a CNC controller. Figure 20 shows the overall architecture of the STEP-compliant CAD/CAPP/CAM/CNC scenario.

A follow-on pilot project sponsored by STEP Tools undertook to demonstrate STEP-NC at participating sites. In January 2003, a demonstration at NASA’s Jet Propulsion Laboratory showed the GibbsCAM STEP-NC plug-in generating NC code for milling from an AP-238 input file (Anonymous 2003b). Tests showed a reduction in programming time from 105 min to 12 min. In June 2003, a demonstration at NIST showed the MasterCAM STEP-NC plug-in generating NC code

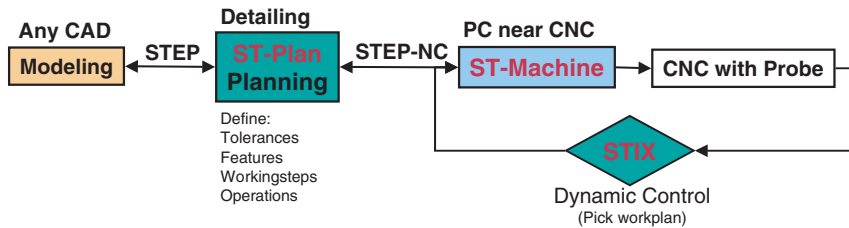


Figure 20. STEP-compliant CAD/CAPP/CAM/CNC scenario (IMS STEP-NC Consortium 2003).

for surface milling and probing from an AP-238 file. This demonstration included handling of Boeing/McDonnell-Douglas AIMS-PE parametric surface definitions.

**4.6.3 Boeing experience.** In the aerospace industry, Boeing manufactures parts with complex surfaces on a variety of five-axis CNC workstations. Current practice is that a CNC machine cuts a part based on part programs following the ISO 6983 standards that define specific axis movement. The differing five-axis configurations mean that each part must be post-processed to a specific CNC machine configuration—a costly and time-consuming task.

Following their early success in using STEP as the data-exchange format to work with the three engine manufacturers for Digital Pre-Assembly on the 777 and 767–400 Extended Range Programs, Boeing conducted a pilot program to use STEP-NC to program the CNC with higher-level cutter motion data, instead of axis movement data. Being ‘machine neutral’, the cutter motion data can be used by machines of differing geometry. In their pilot program, a Catia V5 Section 3 (CL) file is converted to a STEP-NC AP238 Part 21 file, which is then converted in a configuration-independent part program file containing i, j, k cutter descriptions. The conversion into i, j, k cutter descriptions can be of a (1) BCL (Basic Control language), (2) Siemens 840D version of G-code, or (3) Fanuc version of G-code formats.

#### 4.7 Research work in New Zealand

Most of the research work carried out in the Manufacturing Systems Laboratory of the University of Auckland aims to achieve a STEP-compliant CAPP/CAM/CNC environment. There are three pieces of work carried out in this group. The first is the development of a STEP-compliant CAPP system for collaborative manufacturing (figure 21) (Xu and Mao 2004a, b). The system uses STEP (Part 21) and STEP-NC (AP238) standards to construct a universal data model. Two process-planning modes—‘integrated’ and ‘interfacing’—are supported. STEP physical files and early binding XML documents are used as the default data model to unify data formats at the design, process-planning and manufacturing phases. A user interface allows process planners to work with Workingsteps. In order to support collaborative manufacturing between geographically dispersed designers and manufacturers, the system also employs the technologies such as a three-tiered network architecture,

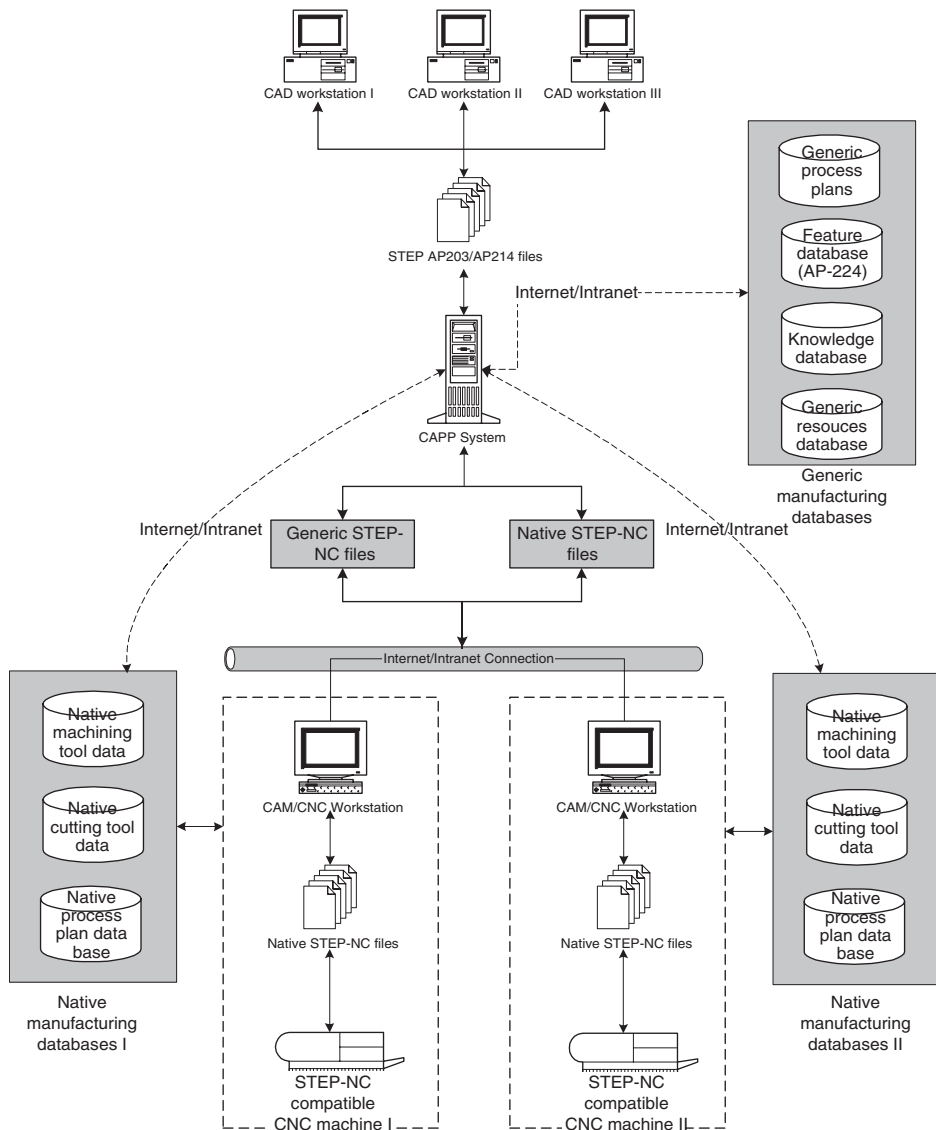


Figure 21. STEP-compliant collaborative manufacturing model (Xu and Mao 2004a).

ASP, ActiveX controls, IIS, OpenGL and XML for data exchange across the Internet.

The second piece of research focuses on the development of a proposed STEP-Compliant 'Adaptor' (Wang and Xu 2004). A major part of the work is to develop a data structure for native manufacturing databases that can fully describe CNC machine tools in a digital format. The canonical characteristics of machine centres developed by NIST have been used as the basis for the development work. The current focus of research has been on incorporating information documented by the draft STEP AP240 standard (ISO/DIS 10303-240 2004). This is because STEP AP240 includes not only the required information for supporting NC

programming, but also the shop-floor information such as machine setup and part loading instructions.

A G-Code free, STEP-compliant machining scenario has been realized by the same research group (Xu 2005). The research work is conducted in two parts. The first involved retrofitting an existing CNC machine with a more open platform control system—Compumotor Motion Control system, which is capable of interfacing with other CAPP/CAM programs through languages such as Visual Basic, Visual C++ and Delphi, whereas the control system is programmable using its own motion control language—6K Motion Control language. A library of 6K functions has been developed to cater for different machining operations. The second part of the research is the development of a ‘STEPcNC Converter’, which can understand and process STEP-NC codes, and interface with the CNC controller through an interface. The Application Interpreted Models are used.

#### **4.8 Research work in other countries**

Work on XML-based high-level NC data modelling for a Web/XML-based manufacturing data-management system has been carried out by the Hokkaido University in Japan. An Open CAM Framework has been designed by a number of parties including Komatsu Engineering Co., Ltd to construct CAM systems that allow users to embed machining knowledge and resource information necessary for machining. Inputs to this system are STEP AP224 machining features (ISO/DIS 10303-224 2001).

To make CNC controllers more accessible to the users, a new low-level CNC language called Base Numerical Control Language (BNCL) has been developed (Fortin *et al.* 2004). The architecture is designed based on two concepts: the BNCL virtual machine, which acts as a virtual microprocessor, and the BNCL virtual hardware, which is an abstraction of the machine tool. This low-level language is meant to improve the STEP-compliant information flow from CAM to CNC.

Work carried out at the Shandong University, China involves the development of a STEP-NC-based process-planning model (Liu *et al.* 2004a, b). This model has three tiers of planning activities: offline, online and real-time planning, performing tasks of machining feature generation, Workingstep generation and Workplan formation, respectively. A reasoning module has been developed and used for optimization at each tier.

### **5. Discussions and challenges for STEP-NC**

Results of the research just described and technical discussions at standards committee meetings have brought to light several issues that are being debated or remain open. These include data representation, such as implementing ISO 14649 v. AP238 or STEP Part 21 physical files v. Part 28 XML, as well as technical issues such as feedback to upstream processes, tool modelling and selection, dealing with tolerance information and the use of a generic CAPP language. These issues are described in the following sections.

Table 2. Comparisons between an ARM and AIM model.

Comparison criteria	ISO 14649 (ARM) model	ISO 10303–238 (AIM) model
Storage needed	~10 times less than AIM	~10 times more than ARM
Programming	Easy	More complex
Human readable	Difficult	Almost impossible
Compatibilities with STEP	Partly compliant	Fully compliant
Data consistency	Original design information is abandoned	Original design information is preserved

### 5.1 AIM vs. ARM

As mentioned in the introduction, there are two different ISO subcommittees working on the STEP-NC standard with two different focuses. ISO TC 184/SC1 works on the ISO 14649 (ARM model), whereas ISO TC 184/SC4 works on the STEP AP-238 (AIM model). The main difference between these two models is the degree to which they use the STEP representation methods and technical architecture (Feeney *et al.* 2003). Table 2 compares these two models.

ISO 14649 and ISO 10303-238 can be viewed as two different implementation methods of the STEP-NC standard. The ISO 14649 standard is more likely to be used in an environment in which CAM systems have exact information from the shopfloor, whereas STEP AP-238, as a part of the STEP standard, is more suitable for a complete design and manufacturing integration.

The ISO 14649 standard has no mechanism to incorporate other types of STEP data, hence making bi-directional data flow between design and manufacturing more difficult. Unlike ISO 14649, STEP AP-238 encompasses all the information from STEP AP-203 and AP-224 plus an interpreted model mapped from ISO 14649. Hence, bi-directional data exchange is enabled.

However, STEP AP-238 is not without its problems. One problem is that the STEP Integrated Resources used in AP238 are not adapted to application areas; hence the data in its files are fragmented and distributed. It only provides an information view of the data, whereas the ARM provides a functional view of the data. The files can also become much larger than an ISO 14649 file. In order to work with AIM files, tools and/or libraries such STIX developed by STEP Tools Inc. can alleviate data-handling chores for developers (<http://www.steptools.com/stix>). STEP AP-238 files are not as easy to decipher as ISO 14649 files. The structure of AP-238 files is more complex and may require more storage space.

### 5.2 Part 21 vs. Part 28

Part 21 and Part 28 are the two common implementation methods for EXPRESS defined STEP data. The Part 21 file format is currently the most popular implementation method. It uses the minimalist style in that the same information is never written twice so that there is no possibility of any contradictions in the data. At the same time, the size of a Part 21 file is made small. Generally speaking, the Part 21 file format has provided sufficient syntax to represent STEP entities in text.

There may be some doubts about the existence of Part 28. A number of benefits can be envisaged by adopting XML through use of Part 28 (Kimber 1999).

1. XML defines a generic and robust character syntax for representing structured data objects;
2. XML provides facilities for the syntactic validation of documents against formal rules, potentially enabling the validation of some or all of the constraints in EXPRESS schemas using generic XML validation software;
3. because XML is inherently extensible and flexible, it should enable new facilities in the interchange representation that Part 21 cannot provide;
4. as XML is supported in most Web browsers, it is possible to exchange/view/edit STEP/EXPRESS entities or instances via hyperlinks through Web pages;
5. as XML is normatively tied to an existing ISO standard—ISO 8879 (SGML), it is an acceptable candidate for full use with other ISO standards without the need for further standardization effort;
6. by using the XML early binding approach with EXPRESS schemas, the entities defined in EXPRESS schemas can also be represented in an XML document as well as the data;
7. a piece of XML codes can fully and independently represent an EXPRESS entity instance, which is important when constructing databases for EXPRESS/STEP entity instances;
8. XML provides basic verifying methods through Data Type Definition (DTD) and more recently XML Schemas (ISO 10303-28 2002, Lubell and Frechette 2002);
9. XML applications can be integrated in many different systems with ease;
10. there are a number of free or commercial XML interpreters available, such as MSXML from Microsoft for Windows applications and SAX (Simple API for XML) for Java applications; and
11. as XML is becoming a popular technology, its use in ISO 10303 may help to increase the public awareness of STEP and EXPRESS.

As shown in table 3, Part 28 has many advantages over Part 21. However, the Part 21 syntax predates Part 28 by a number of years, and now most STEP-compliant applications and developing tools are based on the Part 21 definition. Part 21 files have a stronger presence in CAD systems.

### ***5.3 Feedback to upstream processes***

Providing feedback from manufacturing to design, process planning, and quality control promises improved products and significant cost and timesavings. G-code format data are useful passed forward to machining but are useless for feedback (except for changed G-code). The STEP-NC data format is better for providing feedback, for two reasons.

First, STEP-NC data include design data and include process plan data at a much higher level than G-codes. If downstream processes are able to write these data as well as read them, they can feed back designs and plans in the same format in which they are received. Second, in STEP-NC, probing sets the value of

Table 3. STEP Part 21 compared with early binding approach of STEP Part 28.

Comparison criteria	STEP Part 21	Early binding approach of STEP Part 28
Abilities of representing EXPRESS instances	Yes	Yes
Extensibilities	Weak	Strong
Storage required	Less	More
Structure	Cross-link based	Hierarchy structured
Data repetition	No	Yes
Human interpretable	Partly	Completely
Difficulty of interpreting	Hard	Easy
Exchange via Web pages	Can only be done via an individual physical file	Can exchange any part of the document in its hierarchy structure

an `nc_variable`; while not designed for feedback, the `nc_variable` could be returned as feedback to process planning. G-codes (although they do support the execution of probing) do not support feedback of probe data outside the controller executing the G-codes. In addition, STEP integration might be extended to include feeding back production run data such as actual tool selection and cutting time by modelling these data using established STEP techniques. If these data were available in process planning, they would enable long-term optimization and better NC visualization and verification. If the data were available in design, they would facilitate improving design-for-manufacturing techniques and determining the consequences of design choices on manufacturing cost.

Feedback links are shown in figure 1 as the dashed arrow, which indicates that, while conceptually possible, this promising data path has not been adequately explored. The data model should be reviewed for its applicability to upstream feedback, using compelling scenarios and research pilot projects as drivers. In feedback from manufacturing to design and process planning, there is a catch. To be useful, the reasons for changes must be fed back along with the changes. Only natural language is currently available for giving reasons, so only humans will be able to use the feedback. For automated handling of feedback, machines must be able to deal with reasons. Developing formal languages for stating reasons, integrating them with STEP-NC data, and building systems to process them are fertile areas for research.

#### 5.4 Tool modelling

STEP-NC models tool requirements, namely those aspects of tooling needed for particular machining operations. These requirements are different from tool descriptions, such as those for particular tools in a tool inventory or catalogue. The fewer requirements specified by a STEP-NC process plan, the greater the freedom enjoyed by the CNC to select a particular tool at run time.

Conversely, if a STEP-NC process plan specifies comprehensive tooling requirements associated with a particular tool, that tool must be available at run time, or the plan cannot be executed.

Deferring tool selection to run time allows cutting setups to be changed immediately prior to the cutting process, indeed during pauses in cutting, avoiding the needless regeneration of STEP-NC programs after minor tooling changes such as sharpening. Unless a toolpath is given in the STEP-NC file, handling a tool whose measured diameter differs slightly from its nominal value is not a problem. The controller uses the measured value when generating the toolpath. However, STEP-NC has no way to specify an offset when a toolpath is given, so changing the tool size slightly requires regenerating the toolpath in order to produce the same geometry on the part. In this regard, STEP-NC has less functionality than ISO 6983, which does provide for specifying an offset. This functionality should be added to STEP-NC so that minor changes in available tooling do not require that the STEP-NC file be regenerated.

ISO 14649 parts 111 and 121 describe tool requirements for milling and turning, respectively. ISO 10303 AP238 maps these on to integrated resources from ISO 10303 Part 41, and also introduces new elements. A related standard, ISO 13399, is a draft data model for tool descriptions, such as those found in a tool catalogue or as documentation accompanying purchased tools. It contains conceptually much of the same information as in STEP-NC, although its purpose is different. ISO 14649 does not reference ISO 13399, nor are the two harmonized. The consequences of the lack of harmonization are illustrated by the following scenario: a shop owner purchases several end mills from a supplier, each with a small CD-ROM that contains its ISO 13399 description, and loads the CD-ROMs into his tool management system. The shop programmer plans the machining job in a STEP-NC CAM system that has been integrated with the tooling database and generates a STEP-NC program. The shop machinist loads the STEP-NC program into a STEP-NC CNC that is also integrated with the tooling database, and begins the job. However, the CAM vendor (when converting ISO 13399 to ISO 14649 data while writing the STEP-NC program) and the CNC vendor (when reading the program and performing the reverse conversion) have different rules for interpreting effective cutting length. The tool selected by the CNC is shorter than the CAM system expected. When the controller tries to make a deep hole, the tool holder is mashed into the part.

This scenario illustrates the problems caused by incompatible standards. One important issue is the need to harmonize both ISO 14649 and ISO 13399. Presently, the committees responsible for these standards are working to resolve this issue. Such a resolution will greatly improve the degree of integration between tool-management systems, process-planning software and machine-tool control.

The method of marrying data in a STEP-NC program to data representing the tools actually resident on the machining centre has not been addressed in ISO 14649. This need is acknowledged explicitly on the first page of ISO 14649 Part 111, but it is put out of scope. This is a weakness in the standard. A general solution is to allow a tool to be specified in a STEP-NC file by giving any of (1) the id of a specific instance of a tool, (2) the name of a tool type whose characteristics are given in a catalogue or (3) the tool characteristics (the current STEP-NC method).



### 5.5 Tolerancing issues in STEP-NC

Tolerancing is one primary means to guarantee part interchangeability and functionality. It also has a far-reaching effect on manufacturing processes in terms of both cost and productivity. The need to integrate product and process data and to be able to update the tolerance information based on the current level of processing is important to the end-users. Having tolerances available when generating machining commands or even at run time is essential to enabling adaptive machining. Some commercial systems such as MDSI (Manufacturing Data Systems 2004) have used their proprietary tolerancing approaches to provide adaptive cutting speeds based on the tolerances and machine dynamics resulting in shortening the machining time. However, tolerance issues have not been adequately addressed in the STEP-NC standards, partly because of the uncoordinated work in other parts of STEP for representing tolerances. This is reflected by the isolated work in developing standards such as AP203 e2, AP219, AP214 and AP224, and the effort of ‘porting’ the tolerances in some of these APs into ISO 14649, AP238 and AP240. In recent years, some work has been carried out to integrate tolerances into the product model. Two different approaches have been discussed, introducing ‘measuring features’ as new geometry items and introducing the ‘criteria’ concept which helps to interpret tolerance information. The criteria are defined based on a geometrical item, which might be a feature (IMS STEP-NC Consortium 2003). Tolerance harmonization has also been under way for some time. The technical issues in tolerance harmonization have been resolved, i.e. those for design (AP203 and AP214), those for manufacturing (AP224 and AP238) and those for inspection (AP219). However, there is still a long way to go before the harmonized tolerances are put into place in these APs.

All of the above effort seems to have fallen short of acknowledging and addressing the differences between tolerances of different types and purposes. For product assembly, tolerance requirements of a finished product are usually allocated to dimensions of individual parts and/or their design features. The allocated part tolerances are thus called *design tolerances*. For part manufacture, design tolerances are often converted into *manufacturing tolerances*, i.e. the tolerances of intermediate working dimensions in part fabrication processes, e.g. in machining processes. These two types of tolerances in many cases differ from each other. Take the part in figure 22, for example (Ding *et al.* 2004), where the product design dimensions ( $D1$ ,  $D2$ ) with their respective tolerances ( $T1$ ,  $T2$ ) are shown in figure 22(a). The manufacturing process involves two operations to

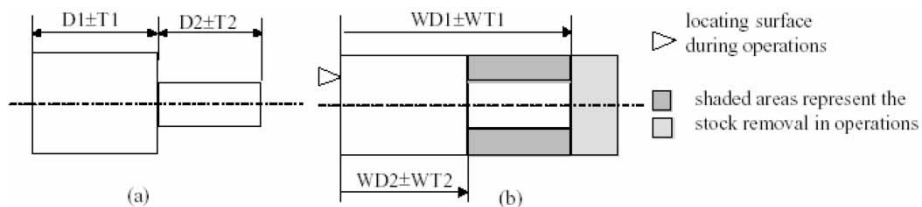


Figure 22. Design tolerances and manufacturing tolerances (Ding *et al.* 2004).

remove material and generate resultant dimensions (figure 22(b)). Accordingly, there are two working dimensions (WD1, WD2) that are the direct results of these two manufacturing operations. The task is then to establish the relation between D1, D2 and WD1, WD2 and to transform design tolerances (T1, T2) to those of manufacturing (WT1, WT2).

From the standardization point of view, it is desirable and also feasible to have one abstract model of tolerances, i.e. one EXPRESS schema. However, tolerances present in different Part 21 files generated based on different APs need to be 'flagged' unambiguously, be it design tolerances based on AP203e2, manufacturing tolerances based on ISO 14649, AP238, AP240 and maybe even AP224, and inspection tolerances based on AP219. While relating/converting tolerances of different types is altogether another challenging task, distinctions among them must be made clear.

### 5.6 Generic CAPP language

Certain features of process plans for discrete manufacturing are found in almost all domains at almost all hierarchical levels. It would be extremely useful if a generic process plan model incorporating these features could be written that could then be used by models of process plans applicable to specific hierarchical levels in specific domains. The current unfortunate situation is that these features are being modelled multiple times in different ways. By using a generic process-plan model, it will be much easier to build interoperable systems. This approach is implemented and proven to work in FBICS (Kramer *et al.* 2001, 2004). The generic language is ALPS. It is used by the plan model for the cell level (at which an entire part is considered) and by the plan model for the workstation level (at which one fixturing of a part is considered).

The executable parts of manufacturing process plans (the core of most plans) can be represented generically by a directed graph of nodes, each of which represents either a control structure or an activity to be performed. The control structures are used in determining the order in which the graph should be traversed. Types of control structure typically found in discrete manufacturing process plan models include (1) sequential; (2) non\_sequential; (3) parallel; (4) selective; (5) alternative; and (6) loop.

Both STEP-NC and STEP 10303 AP240 are being developed for process planning. The former is meant for micro-process plans, the latter for macro-process plans. STEP-NC includes all of the above as (1) the *its\_elements* list of a workplan, (2) *non\_sequential*, (3) *parallel*, (4) *selective*, (5) *if\_statement* and (6) *while\_statement*. However, AP240 includes only (1) *sequential*, as the activities attribute of a *process\_plan\_version*, and (5) *alternative*, doubly modelled as the *alternate\_plan(s)* of a *part\_version* and the *alternate\_activity* of an activity. ALPS includes most of the above plus semaphore and timer control structures.

Additional useful items which may be defined in a generic process-planning model include: variables, numerical expressions and operators (e.g.  $a + b$ ), and plan parameters (which are analogous to function call arguments). The (obviously desirable) integration of STEP-NC with AP 240 would be greatly facilitated if a generic process-plan model were built and used by both.

### **5.7 Harmonization of STEP-NC information models**

The use of STEP-NC for CAD/CAPP/CAM/CNC brings the benefit of better integration for information models from design to manufacture avoiding semantic errors giving an end to the translation between proprietary and non-proprietary formats. However, the changing specifications of the various ISO information models to represent the various geometric elements (AP203/AP214), features (AP224), process planning (AP240), CNC equipment (AP238) and AP219 (inspection analysis) together with the various parts of ISO 14649 provides a wide range of different and sometimes contradicting definitions for representation of product and manufacturing models in CAD/CAPP/CAM and CNC. This is already evident in the STEP-compliant NC definitions with the US utilizing AP238 and Europe using ISO 14649 for CNC model development.

### **5.8 Interoperability in the CNC programming process chain**

For STEP-NC-compliant manufacturing to succeed, the various CAX solutions will need to be interoperable via product and manufacturing model data providing both information and knowledge sharing across the CAD to CNC process chain. This requires the machine tool users to trust the process-planning mapping linkages between the manufacturing features in the product model and the process machining representation according to ISO 14649 standards in the manufacturing model. This need for a consistent and common view is reiterated by the ISO 14649 standard, which uses features closely resembling the well-established ISO 10303-224 (AP224) standard. As STEP-NC features have a terminology and structure, which closely resembles AP224 features, it causes the additional disadvantage of mapping AP224 features to those in STEP-NC features, which is an overhead for CAX solutions from the information model integration viewpoint. Therefore, the authors believe that the need to make STEP-NC features consistent with the AP224 standard is vital to their success.

### **5.9 Intelligent controllers**

In addition to the major aim of STEP-NC to provide bi-directional information transfer between the CAX software solutions and the intelligent CNC, a major shift in culture and user belief is needed to trust the new breed of intelligent controllers to translate feature-based conversational programming to the correct tool-path at the machine. This is recognized as a paradigm shift where the equivalent of today's post processor functions at the offline CAD/CAM system will take place at the machine leading to the end of G & M codes. It should be recognized though that this paradigm is not new, as commercial products such as Mazak's CAMWARE already successfully integrated their offline CAMWARE system with Mazak CNC machines, with Mazak-defined machining features. In the CAMWARE system, Mazak feature information is totally consistent with the feature-based machining routines at their Mazatrol CNC controller, and Society of General Microbiology toolpath simulation information and machining knowledge is trusted and proven. Mazak also have the ability to program a part at the Mazak CNC controller or offline, thus enabling bi-directional communication, the essence of STEP-NC.

Though this shows that the ideas behind STEP-NC's feature-based machining approach are feasible, it brings a number of major challenges to CNC control vendors and CAx vendors to work together to transfer the knowledge of the CAM systems to the CNC controller combined with CNC vendors providing process machining knowledge of their machining toolpath algorithms to enable CAx vendors to simulate the actual toolpaths offline.

### **5.10 Integrated CAD/CAPP/CAM/CNC using product and manufacturing models**

The developments and applications of STEP-NC have made invaluable contributions with the adaptation of CNC controllers, CAD/CAM and CNC shopfloor programming systems to take advantage of contemporary technologies. The authors believe that though these developments have provided an initial stimulus to promote the standard in current commercial systems and CNC controllers, there is also a need to consider the generic knowledge and information requirements (models) to support the total process chain from design through to CNC manufacture. This process chain also needs to be considered through from an interoperable viewpoint enabling CNC programming to be initiated at the design, manufacturing planning and CNC machine levels. Thus, there is a need to define the product model information including design and manufacturing intent for each CNC part based on ISO standards, which can be populated from design office through to the shopfloor.

For the ethos of STEP-NC to be successful, the necessity to identify a consistent model definition of the product that maps on to a manufacturing model is critical. Product modelling (Xu and He 2003) is recognized as a well-matured area of research and has been pivotal in defining engineering data-management systems to support the concurrent engineering process. Manufacturing modelling (Young *et al.* 1999), on the other hand, is still at an earlier stage of development, but its need is as vital, with standards needed to map CNC resource and process information on to the product manufacturing requirements. The US Super Model project has tried to address this goal with the use of an AP238 integrated CNC model consisting of ISO 14649, AP203/AP214, AP224 and AP219, and may well yet be the total solution for product modelling.

### **5.11 Function blocks and NCML**

Two other technologies that are related to CNC also emerged at the turn of the 21st century, Function Blocks (IEC TC65/WG6 1999) and NCML (Numerical Control Markup Language) (Ryou and Jerard 2001, Jerard and Ryon 2002). Function blocks are a new IEC standard for distributed industrial processes and control systems. They are based on an explicit event-driven model and provide support for data flow and finite state automata-based control. Based on previous research (Zhou *et al.* 1999), function blocks can be used as the enabler to encapsulate process plans, integrate with a third-party dynamic scheduling system, monitor process plan during execution, and control machining jobs under normal and abnormal conditions. They are suitable for machine-level monitoring, shopfloor execution control and CNC control, and are therefore seen as an attractive complementary technology for STEP-NC-enabled adaptive control or close loop manufacturing.

NCML is based on XML. Elements of the language are defined in a Document Type Definition which is suited for the electronic exchange of information between buyers and sellers of custom machined parts capable of being produced on NC machines. Functionally, NCML is a description of a process plan for machining the part which can be easily translated into tool paths by a modern CNC machine tool (Ryou and Jerard 2001, Jerard and Ryon 2002). Though some of its functionality is seen as similar to that of ISO 10303 Part 28, NCML offers does offer another alternative for distributing NC data over the Internet in support of a collaborative manufacturing scenario. It has an added advantage of better supporting e-commerce. What are not known yet are the issues of STEP-compliance, or rather that of how to make it STEP-compliant.

## 6. Conclusions

The enhancements in open control coupled with modern computer technology have provided the basis to re-examine the way in which CNC machines have been programmed during the last 50 years. These enhancements, combined with the application of new STEP standards in manufacturing, have provided a valuable stimulus to raise the awareness of controller suppliers, CNC machine-tool manufacturers, and CAx software vendors to develop new CAM and CNC software products that have the possibility to bring about a new era for CNC manufacture in the 21st century.

The survey is believed to be comprehensive, but by no means inclusive. Unlike other reviews that have been published, this paper tries to provide readers with a more technical insight into the various research projects carried out by the major research groups worldwide. A relatively high magnitude of funding strength over a number of STEP-NC-related projects during a short span of time sufficiently demonstrated the importance of the STEP-NC-related development work. Participation of, and collaboration among, a wide variety of organizations such as end-users, academic and research institutions, and manufacturers of CAM systems, controls and machine tools, echoes the significance and relevance of this work in particular from the industry perspective. Some research has yielded promising results and a number of public demonstrations have been carried out in countries such as Germany and the USA. Most of them had their industry partners involved, and many play a main role in the demonstration. Continued and collective efforts made by many research groups, consortiums as well as industry partners are still greatly needed to take up the new challenges and bring about the full benefits of STEP-NC-enabled technologies.

Discussions in this paper over a number of critical issues concerning STEP-NC provide 'food for thought' and point out the potential research topics and technical challenges. It is believed that the use of STEP-NC, if successfully developed and marketed, will require a paradigm shift in programming together with a culture change for machine-tool users being required to trust the programming of their manufactured parts to intelligent CAM systems CNC controllers. This change will become a reality only if company owners see cost reductions in the design to manufacturing process chain which enable lead times to be reduced with component prove out minimized, part quality improved and machine utilization increased. It is also important to realize that while STEP-NC is the right general approach, its chances

of success in its current form are modest. There is still ambiguous, incorrect and missing information in various standards. Many inconsistencies among standards remain to be resolved. A large amount of systems-building work is needed to make STEP-NC-related technology commercially viable. However, the authors believe that STEP-NC is the right approach; the challenge is to convince the users.

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