Chapter 9
Implementing STEP-NC: Exploring Possibilities for the Future of Advanced Manufacturing

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Abstract This chapter contains a summary of the current state of the ISO data model ISO14649 for Numerical Controller also known as STEP-NC. It details the reasons and need for an industrial STEP-NC paradigm shift by showing the benefits that would be immediately realizable using currently available tools and knowledge. Specific focus is given to the SPAIM application as it is one of the most advanced STEP-NC enabling applications available today that allows realizing those benefits. In considering the future possibilities of STEP-NC and the need for continued implementation, four important and complex topics are addressed. These topics would enable an increase in: interoperability through hybrid manufacturing environments, manufacturing supervision and traceability, flexibility and efficiency with high knowledge and information transfer as well as production optimization and simulation in multi-process manufacturing. Finally, a brief synopsis of the systems and components necessary for machine migration to STEP-NC using the SPAIM enabling application is given.

9.1 Introduction

9.1.1 STEP-NC, the Data Model

STEP-NC, known formally as the ISO 14649 standard, is an offshoot of the STEP standard (ISO 10303) which is centered around automation systems, representation of product data and exchange specifically between Computer Aided systems (CAx). However, unlike STEP, the distinction of STEP-NC is that it focuses primarily on the interaction between CAx systems and the numerical controller (NC).

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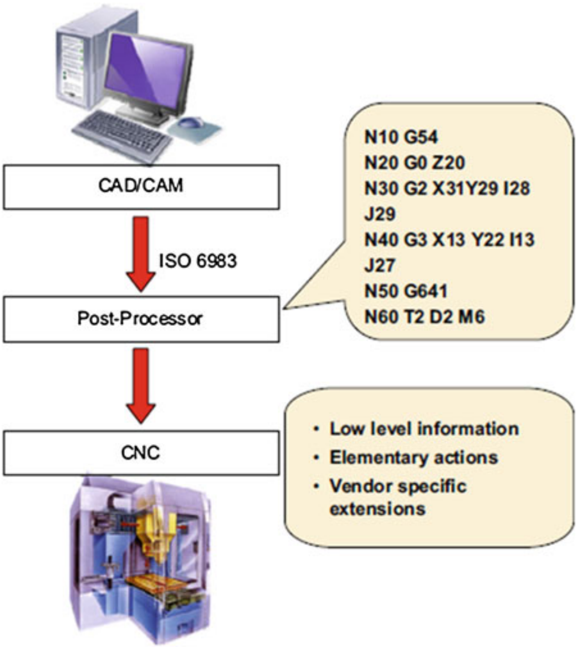

Fig. 9.1 Current G-code programming

It aims to provide a seamless link with CAx systems while taking a strong perspective from the machine and machine-controller point of view. Using the defined backbone of EXPRESS data modeling language, STEP-NC shifts the focus towards a very important part of manufacturing, the machine-tools that are responsible for making the carefully designed parts.

The birth of STEP-NC is attributable to the need from industrial manufacturers as the revolution of the CNC machine continued. After having attained efficient and low cost productions with the CNC, manufacturers seek to meet the needs of the ever changing market by increasing flexibility, adaptability and improving productivity. To this end, the research community has been invaluable in providing new solutions, technological improvements related to cutting tools, machine-tools and CNC performances. However, little focus was placed on the current programming standard, which makes the link between the perfect CAD model and the real machined product as well as supporting machining orders and intelligence of CAM processing and simulations.

This current machine-tool programming standard is the ISO 6983 (G-codes) dating back to the early 1980s [1]. This standard with low level information describes elementary actions and tools moves, strongly reducing possibilities at the CNC level. Its linearly sequential nature (Fig. 9.1) breaks the CAD–CAM–CNC numerical chain and makes gathering feedback from the shopfloor difficult. The G-codes standard is one of the main limitations to flexibility and interoperability. To counter this limitation and to meet changing market needs, a new standard was required as manifested in the form of STEP-NC [2, 3].

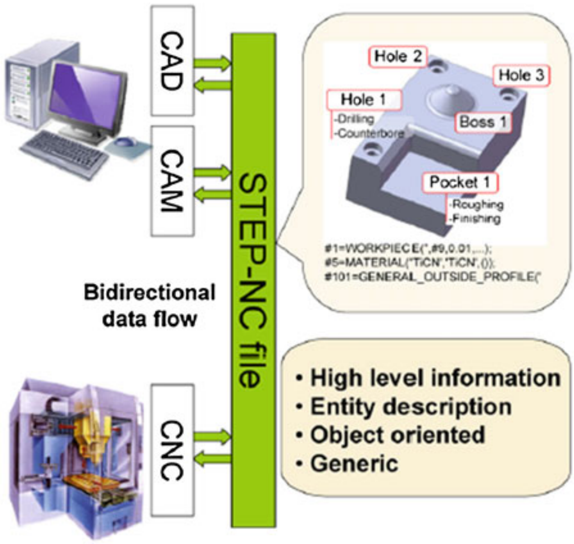

Fig. 9.2 New STEP-NC high level programming

STEP-NC provides new opportunities to support high level and standardized information from the design stage to fabrication by an NC controller. It allows bidirectional data flow between CAD/CAM and CNC without any information loss (Fig. 9.2). ISO 14649 diverges sharply from its ubiquitous predecessor, the G-code, because it does not describe the tool movements for a specific CNC machine as G-code does but rather provides a feature-based data model. A wide range of high level information is therefore made available such as feature geometry, cutting tool description, operation attributes and workplan. STEP-NC as a data model consists of several parts that contain information related to processes in general (Part 10) as well as process-specific parts. At present several processes have been defined including: Milling (Part 11), Turning (Part 12), and EDM (Parts 13 and 14). Other processes such as Additive Manufacturing are currently being defined.

A STEP-NC file, generally used for exchange, is not machine-tool specific and can be used on various machine-tool controllers. A new generation of intelligent controllers can interpret STEP-NC information to generate, simulate and optimize machining toolpaths among other things. The standard also includes a data model for inspection, which aims to provide a closed loop CNC machining environment. With the STEP-NC standard, the CNC controller becomes a central element in the design/manufacturing data chain and some intelligence is transferred from CAM to CNC. For example explicit toolpaths can be computed in the CNC controller itself with the help of an embedded CAM system or trajectory generator. Equally, a machine-tool functional model exists to provide critical information concerning the machine-tool and its controller.

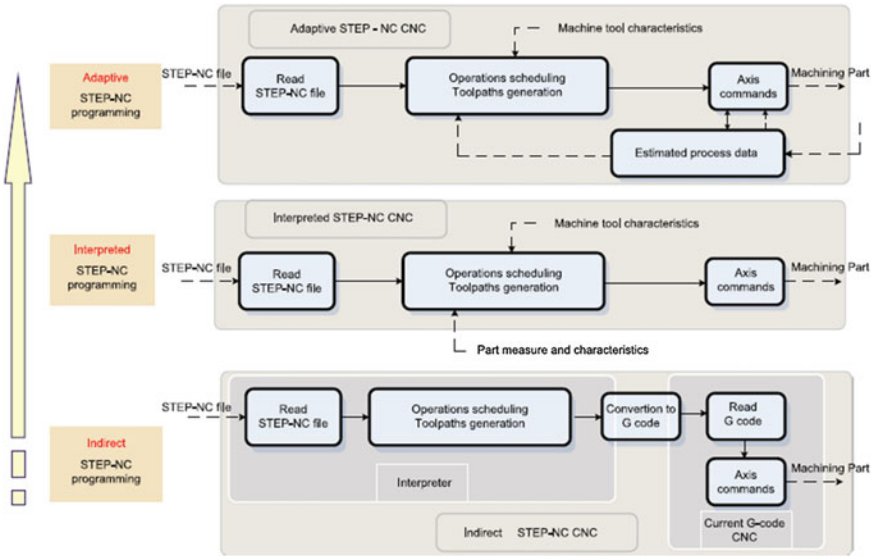

Fig. 9.3 Three-stage evolution towards advanced STEP-NC programming

9.1.2 STEP-NC, Step-by-Step Evolution

Although STEP-NC does promise new opportunities for machine-tool programming, a deep reorganization of the numerical chain at the CAM/CNC level as well as the human element (operator, programmers, CNC developers etc.) needs to take place. High level object-oriented information in STEP-NC has to be treated and executed on the machine-tool which at first requires an interpreter. The interpreter stands as a main part of the extended STEP-NC controller intelligence and carries out toolpaths generation and machining operations scheduling. This is the premise for STEP-NC migration and to realize it requires some new industrial mind shift and training. To this end, three-stages of evolution for STEP-NC in Fig. 9.3 were proposed as a way to gradually, with time and research, migrate the industrial mindset to the STEP-NC paradigm.

The first level is called *Indirect STEP-NC programming*. The use of STEP-NC with legacy NC controllers, that only read G-codes, is made possible. This level combines a standalone application to manipulate STEP-NC, alongside an interpreter embedded in the CNC. The behind-the-scenes STEP-NC is totally transparent from the user and the traditional operations she currently performs. This Indirect level is advantageous because it can very easily be spread on existing CNC equipment and they can profit from some STEP-NC benefits.

The second level is *Interpreted STEP-NC programming* where axis command is directly executed from STEP-NC. Tool and machine-tool functional model is taken into consideration for toolpaths generation and simulations. Integrated bidirectional dataflow between CAD/CAM, as embedded systems, and CNC make this possible. External data such as probing results can be integrated in the toolpath generation process.

The third level is *Adaptive STEP-NC programming* where the NC controller estimates online process data and optimizes machining parameters and toolpaths in real time. This third level is the ultimate goal to achieve and relies on strong STEP-NC programming and interaction with associated systems.

Today, the ISO 14649 standard [4] is built as the Application Reference Model (ARM) of STEP-NC. It offers the opportunity to seriously think about the necessary content to meet the requirement of advanced programming. Some experimental controller platforms, demonstration tools and concept validation algorithms, described in Sect. 9.1.3, exist today as a way to convince the actors of the numerical chain of the interest of using STEP-NC.

9.1.3 Experimental STEP-NC Enabled Prototypes

Existing STEP-NC controllers can be sorted into these three categories of Indirect, Interpreted and Adaptive programming following the evolution levels STEP-NC.

Within the Indirect category and STEP-NC interpreters for G-code machines, (1) one of the first prototypes was realized within the context of the now terminated European STEP-NC project Esprit [5]. In this project, a STEP-NC file is generated by Catia (Dassault Systemes) and Open Mind CAD software. It is then interpreted by a modified Siemens 840D controller. Similarly, a STEP-compliant CNC interface (2) was proposed by the STEP Tools Company [6]. Their ST-Machine software generates ISO 10303-238 files (STEP-NC Application Integrated Model) and works as a front-end application on a current CNC controller. However, despite the generic nature conveyed by the use of ISO 10303-238 files, only a few capabilities envisaged by ARM (ISO 14649) are available. Another STEP compliant interpreter (3), developed at Loughborough University by Newman et al. was envisioned as an Agent-Based Computer Aided Manufacture system (AB-CAM) [7]. This prototype generates ISO 14649 part programs translated to G-code for machining applications. For NC milling applications, software-based CNC prototypes have been developed at the University of Auckland (4) by Wang et al. [8] and (5) by Minhat et al. [9] respectively. The first is an interpreter that stands as a front-end application to commonly used CNC controllers, translating STEP-NC data into G-codes. Conversely, the second prototype is an open CNC architecture based on STEP-NC and function blocks performing the task as a STEP-NC interpreter.

Within the Interpreted category, prototype development has been limited. In this category, the CNC controller does not require G-code as STEP-NC programming is totally integrated. The first prototype (6) was developed at the University of POSTECH in Korea [10]. The platform is based on several independent modules (STEP-NC file generator, toolpath generator, toolpath viewer, machine-tool driving and control). The prototype enables direct control of the motion axes of a scale machine-tool dedicated to laboratory applications. It has not been implemented on an industrial machine-tool but proposes new solutions for axis command control. In a separate development by Xu, a CNC controller prototype (7) was implemented on a retrofitted CNC lathe and enables the realization of G-code free machining scenario [11].

Within the Adaptive category there are no prototypes implemented on any industrial machine-tool. As a first step to facilitate some of the expected features within this category, some proposals and framework have been introduced to help guide development. Shin et al. developed an interpreter for turning applications that converts G-codes files into STEP-NC files [12]. As a result, the introduction of STEP-NC standard for a company does not necessitate reprograming all the existing machining files. Alternately, STEP-NC based machining optimization was proposed by Xu to optimize the machining parameters at CNC level using the high level information of STEP-NC data with explicit toolpaths [13]. Meanwhile, Ridwan et al. introduced a machining optimization framework based on STEP that enables feedrate optimization using process monitoring and control [14]. Strong focus of development and prototyping is still needed to properly demonstrate the mechanism and benefits of this advanced STEP-NC programing category.

One of the primary limitations for STEP-NC has been the lack of programming platforms based on ISO 14649 (ARM) implemented on existing industrial machining equipment. This is one of the key points, not only to demonstrate the capabilities of STEP-NC programming, but also to validate the new models and proposals for the standard. For the realization of this third category and provide an ARM-based implementation on existing machine-tools, the software application elaborated in Sect. 9.2 was proposed and developed. This application is showcased and detailed here because it is one of the most mature systems and has become a central piece in the demonstration of STEP-NC. Many of the future possibilities of advanced manufacturing based on STEP-NC has been developed and validated on this system and it serves as a platform on which future developments would be based.

9.2 STEP-NC Application Showcase: SPAIM

The use of high-level information to communicate with CNC controllers calls for a new organization of the different CAM and CNC modules (i.e. toolpaths generation module, workplan selection module, process parameterization module, etc.). In the case of milling, manufacturing a part consists of removing some material using a cutting tool driven by a NC controller. All the motions and actions such as axis commands are controlled by low-level information generated at the CNC level and all the information is totally transparent to the user. The electrical control and algorithms are not easy to be understood by humans. G-code programming can be seen as a relatively upper-level whose details can be understood by humans but

Fig. 9.4 SPAIM platform at IRCCyN institute

still remains quite difficult to interpret. The low-level G-code information is directly translated by the CNC controller to generate elementary motions and actions on the machine-tool. In a direct contrast, STEP-NC programming is based on high-level information such as feature geometry or definition of the process data. The STEP-NC format is object-oriented and can still be understood by humans.

However, it is still necessary to communicate with the CNC controller and actuate the different parts of the machine-tool. This means that a translation from the high-level object-oriented information to well-adapted and accurate low-level information is necessary. This job, as explained, is carried out by the interpreter. Any STEP-NC interpreter is consequently machine-tool specific as it makes the link between the STEP-NC file and the data required to control the machine's axes. The structure of a STEP-NC interpreter can be built in several ways by using different technologies to compute the high-level information in STEP-NC files to lower-level information for machining. An example of this is seen in SPAIM.

SPAIM (STEP-NC Platform for Advanced and Intelligent Manufacturing) is a platform based on STEP-NC Interpreted Programming approach, which allows an implementation on most industrial CNC controllers such as the one at the IRCCyN laboratory in France (Fig. 9.4). Its implementation associates two main objectives. First it stands as a demonstrator to showcase the benefits of STEP-NC and secondly as a development platform for future STEP-NC research and validations.

STEP-NC object-oriented programming has helped to shift the toolpath generation to the shopfloor level. As a result, some intelligent and decision-making power can be transferred into the CNC controller. By extension, self-learning algorithms could be utilized to produce better quality parts by error compensating [15]. In the SPAIM implementation, the interpreter module is a key part of the controller because it translates STEP-NC manufacturing data into explicit toolpaths using manufacturing feature geometrical characteristics and programming parameterization of each manufacturing step.

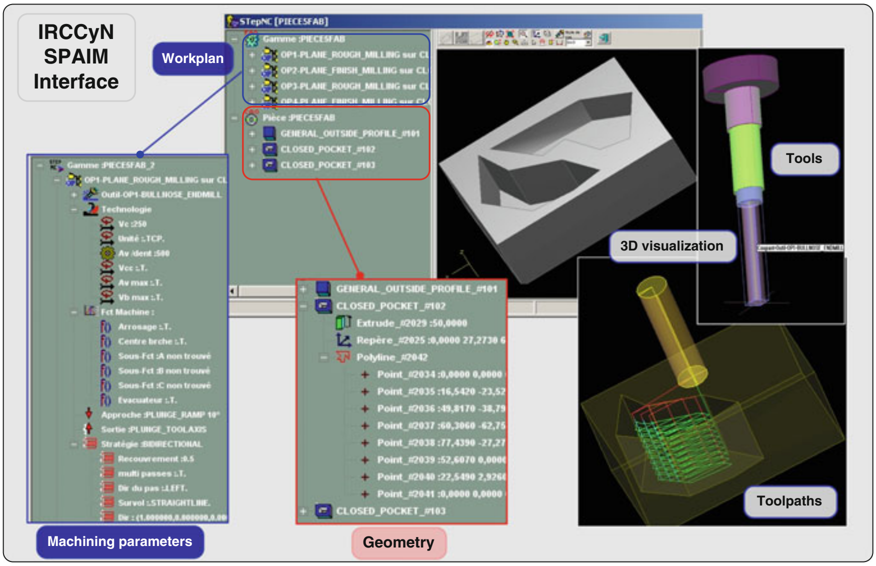

Fig. 9.5 STEP-NC human/machine interface on the NC controller

Although it generates explicit machining toolpaths automatically, the interpreter still calls for user validation before sending the toolpaths to the machine-tool. This stage is considered compulsory because it alerts the user of the expected movements that the machine-tool. Furthermore, the user can check whether proposed toolpath meet the manufacturing constraints. If not, the user can make modifications as necessary. After validation, corresponding output file (G-codes, for first level programming) is automatically executed by the controller.

This platform is composed of a Human Machine Interface (HMI) and several computation modules. The HMI on the NC Controller displays a 3D visualization of the manufacturing data (CAD model, toolpaths, cutting tools, etc.), the machining parameters, and a tree-view of the STEP-NC data (Fig. 9.5). The user can modify these data using the interface. After modification, CAD models and explicit toolpaths are automatically regenerated and the STEP-NC file is updated. Machining can then be executed directly from the interface following a visual validation of the toolpath, machining parameters and modifications.

Following this implementation, the platform can enable any CNC to read and handle STEP-NC data built according to the ISO 14649 standard. This has already been implemented and validated on a high-speed manufacturing machine-tool with parallel kinematics architecture. Designed by Fatronik, this machine called ‘VERNE’ is equipped with a Siemens Sinumerik 840D NC controller [16].

Another version of the platform has also been implemented for a 5-axis machine again equipped with a Siemens 840D controller and it is used for the laser cladding Additive Manufacturing process.

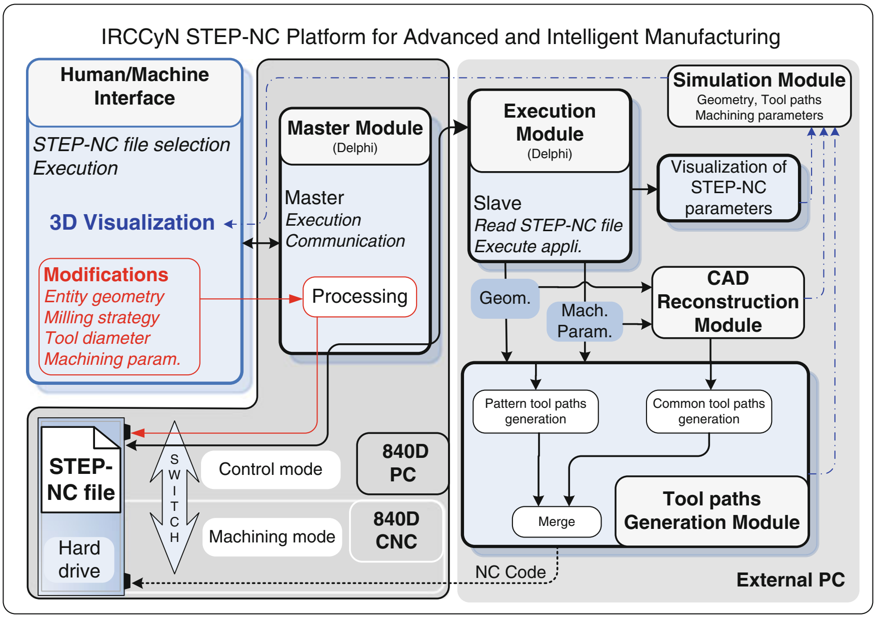

Fig. 9.6 Architecture of SPAIM

9.2.1 *SPAIM Architecture*

SPAIM is composed of several modules controlled by Delphi applications (Fig. 9.6). Some are installed directly on the CNC controller while others are on an external computer to reduce the computation load on the CNC. However, all the modules running on the external PC can be implemented in the CNC computer if its computing capacity allows it. The external PC can be seen as an extension of the capacities of the CNC hardware.

The main modules include:

- *Human Machine Interface*: the user can control the CNC platform using this module. It displays the results of analysis and computations made by the interpreter using data from the simulation module on the screen.
- *Master module*: implemented on the NC controller, this module is directly linked with the HMI and sends the orders to other modules at the user's request. For parameter modification, it locates and replaces the corresponding elements in the STEP-NC data.
- *Execution module*: distributes orders from the Master module via a local or an Internet network. This module reads and analyses the STEP-NC file through the master module and to send the requested information for processing to the toolpath generation module and to the simulation module.

- *CAD reconstruction module*: rebuilds the CAD geometry from the entity description in the STEP-NC data. This automatic tool sends corresponding commands to Delcam PowerSHAPE CAD software [17] for geometry reconstruction. The CAD model is then used by the toolpath generation module to generate common strategies. This module provides feedback from the STEP-NC data to the CAD model as well.
- *Toolpath generation module*: is divided into two components running in parallel. The first handles every common strategy defined in the ISO 14649 standard (e.g. contour parallel, bidirectional, etc.). It uses the toolpath generation module of a commercial software (i.e. Delcam PowerMILL [18]). The second, developed at IRCCyN, handles pattern strategies such as those used for trochoidal and plunge milling toolpaths. According to the manufacturing data, the execution module collects the corresponding toolpath generation module for each machining operation and merges the toolpaths results before sending the NC code to the controller for execution.
- *Simulation module*: sends back the results of the different computations (e.g. STEP-NC data analysis, 3D geometry and explicit toolpaths as a VRML file, etc.) to the HMI for visualization.

The toolpath generation module is based on a vendor component for the generation of common strategies. The SPAIM platform can benefit from the skills and performance of the CAM software. Moreover, it shows that even if the numerical chain is redistributed, all the current knowledge is still needed contrary to the belief of some CAD/CAM vendors. The strong interaction between STEP-NC, CAD/CAM and the CNC is what allows some of the benefits to be obtained.

9.2.2 Benefits of a STEP-NC Enabled Controller

As stated, STEP-NC interpreted programming make it possible to use the STEP-NC standard within existing machine-tools and NC controllers. SPAIM shows the feasibility of this and can be used as a prototype for future implementations. At this first level of the integration of STEP-NC, most of the advantages of STEP-NC at the CNC level are already evident (Fig. 9.7):

(1) STEP-NC data can be read and executed directly on several machine-tools equipped with an interpreter without any modification to the data. This compatibility is enabled by the high-level description of geometry and process data without any specificity to a single machine-tool. All machine-tool information and functional models would be provided by the CNC platform. For example, the execution of the same STEP-NC file on different machine structures would use different spindle speeds, feedrates or toolpaths, because each NC controller would compute the most suitable and efficient parameterization, according to the target equipment.

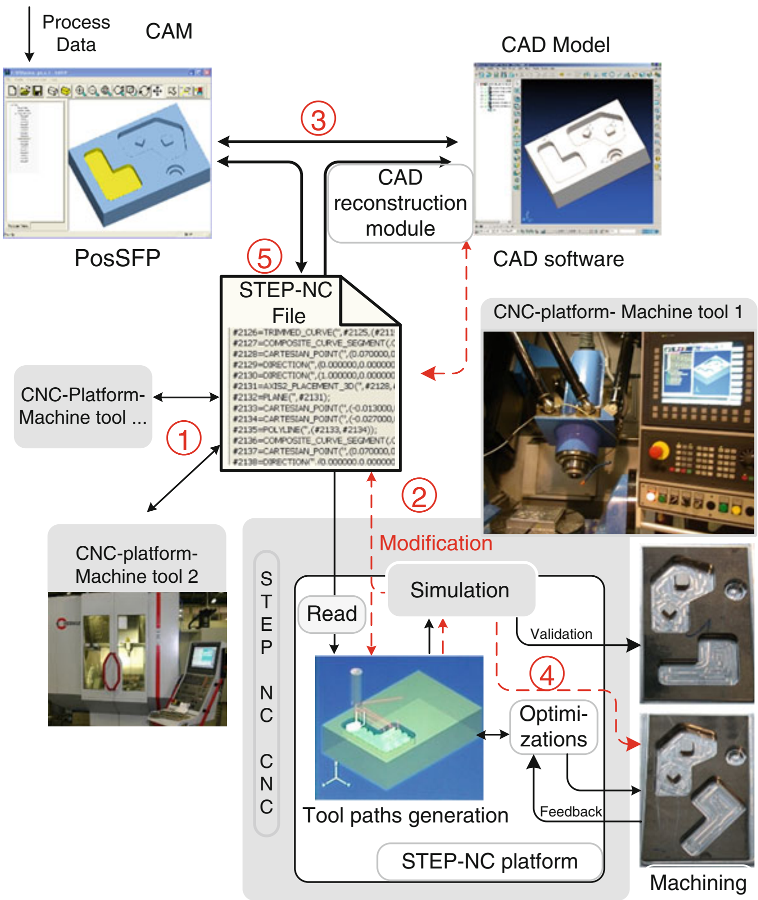

Fig. 9.7 STEP-NC platform numerical chain

(2) Modifications of the geometry and the machining parameters can be achieved at the shopfloor level directly on the CNC HMI. These modifications automatically lead to regeneration of the toolpaths, geometry displays and STEP-NC model tree update. The corresponding STEP-NC data and CAD model are updated as well.

(3) Feedback from CNC to CAD/CAM software is possible since the STEP-NC data is always up to date. Modifications can be done at shopfloor level during the first manufacturing phase of a part. This knowledge feedback enables process planning level to learn and improve the future manufacturing phases.

(4) Optimizing the machining parameters and the toolpaths is easier at the CNC level. SPAIM allows new non-linear optimization based on the STEP-NC data.

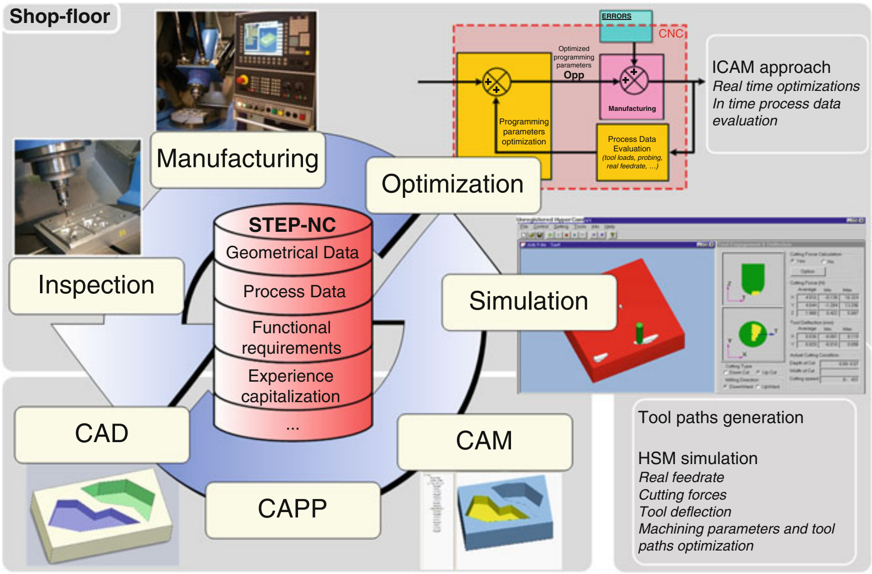

Fig. 9.8 Advanced programming in a comprehensive STEP-NC environment

(5) STEP-NC data transfer file has a small size since it contains only high-level data. This therefore would reduce transfer time making it well suited for Internet-based collaborative manufacturing.

9.2.3 Advanced CNC Programming

The SPAIM platform opens the door for advanced programming methods. As a demonstrator and development platform validation of the ISO 14649 standard, it permits new simulation and optimization approaches to be implemented by taking into account high-level STEP-NC data. Optimization developments previously using g-codes such as a real feedrate simulation module and a tool deflection module can also be included in the STEP-NC framework with some adaptation. The implementation of these modules will be based on research works already done at IRCCyN on 3D solid simulation [19] and tool deflection compensation [20]. As illustrated in Fig. 9.8, SPAIM in its implementation makes each part of the manufacturing numerical chain interoperable. It presents a comprehensive environment dedicated to advanced programming.

Based on this integrated environment, implementation of Intelligent Computer Aided Manufacturing (ICAM) methods is possible and some have already been achieved. The ICAM method was developed to allow toolpath programming optimization based on real-time process information to produce better and more accurate parts. For example, toolpath regeneration based on on-machine inspection

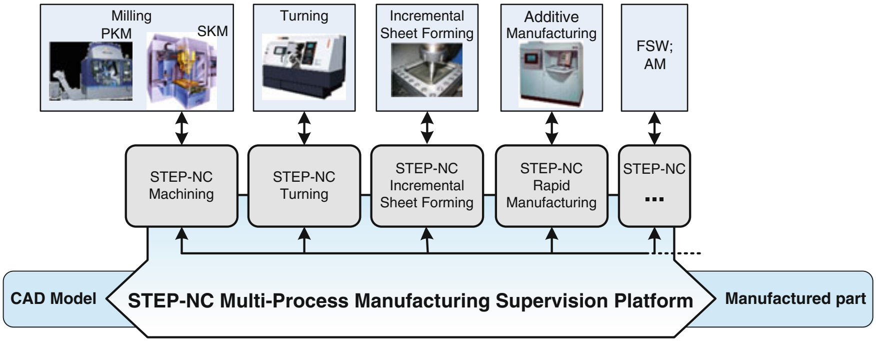

Fig. 9.9 STEP-NC multi-process hybrid manufacturing concept

has been carried out with G-codes with promising results. The real-time adaptations of machining parameters (i.e. feedrate) and toolpaths are possible by using process data evaluation from the CNC controller (motor amperage, delivered power, real feedrate, articular coordinates of the joints, etc.). The scope of future possibility can and should be expanded further and having such a platform at the center of development has many benefits most importantly in closing the loop between once isolated manufacturing systems and sharing of knowledge and experiences between systems and processes.

In fact, it is true to say that developments at IRCCyN on the STEP-NC standard and advanced NC programming methods with SPAIM are not limited to milling. Instead, they include other processes such as additive manufacturing, incremental sheet forming, turning and additive manufacturing processes amongst others. The development and integration of other processes such as wire electro discharge machining is also an important consideration [21]. The development of the STEP-compliant process models and platforms is essential to achieve the goal of interoperability as later discussed.

The long-term purpose of these efforts is aimed at the development of a comprehensive STEP-NC multi-process supervision platform shown in Fig. 9.9. In such an environment, the digital model of a part can reflect the modifications and updates concerning each manufacturing process. Moreover, interactions between two processes will be available and encouraged. In this sense, the manufacture of industrial parts which need a combination of several manufacturing processes will benefit by information sharing leading to part and process optimization. The use of the STEP-NC standard will ensure interoperable and bidirectional data flow between all stages of the product development process. As a result, STEP-NC multi-process supervision concept optimizes the whole design and manufacturing chain from a CAD model to the manufactured product.

All of the opportunities of STEP-NC promise to increase production flexibility, process optimization and efficiency by harnessing the linking foundation that STEP-NC enables as well as enjoying high knowledge and information transfer. Some implementations have been accomplished to help showcase these opportunities

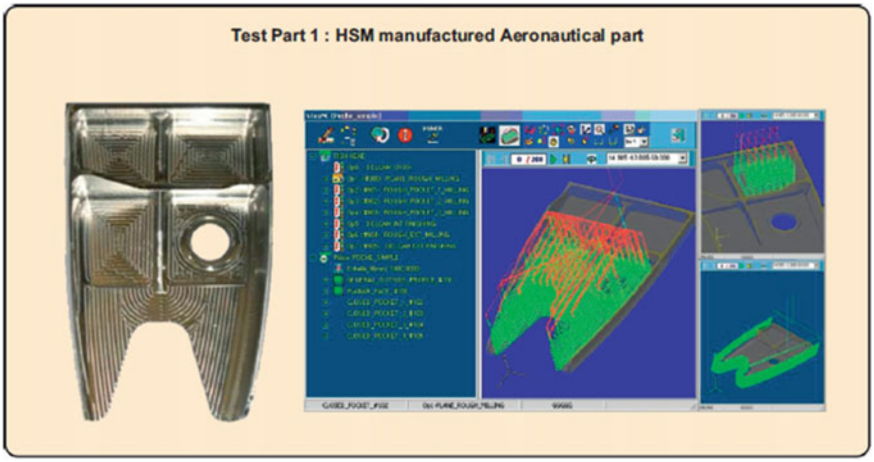

Fig. 9.10 Aerospace STEP-NC test part 'The Fishhead'

(Sect. 9.3). However there are areas that remain scarcely explored that hold tremendous possibility to increase productivity, interoperability and flexibility beyond current industrial capabilities. Some researchers have shown a glimpse into these possibilities by defining frameworks and proposals as to how to best reach these possible new heights [9, 14, 22, 23, 24, 25].

9.3 Current Possibilities with STEP-NC

9.3.1 Flexibility in Milling (+ Other Processes)

Two of the key benefits of STEP-NC highlighted were the ability to read and execute the same part program on multiple machines by using the high-level non-specific data; as well as modify part geometry and machining parameters directly on the shopfloor. These benefits are important because of the increased flexibility they add in terms of part and program modification. Two separate workpieces can be used to describe these benefits. The first is the now famous aerospace testpart, the Fishhead, used around the world for demonstrating STEP-NC (Fig. 9.10). The second is a simple part with pockets, bosses and a hole with counterbore (Fig. 9.11).

These workpieces and the associated scenarios would be applicable to any current industrial CNC that have been made STEP-NC compatible with the addition of the SPAIM application. This would allow them to be capable of Indirect or Interpreted STEP-NC programming and benefit instantly of advanced flexibility.

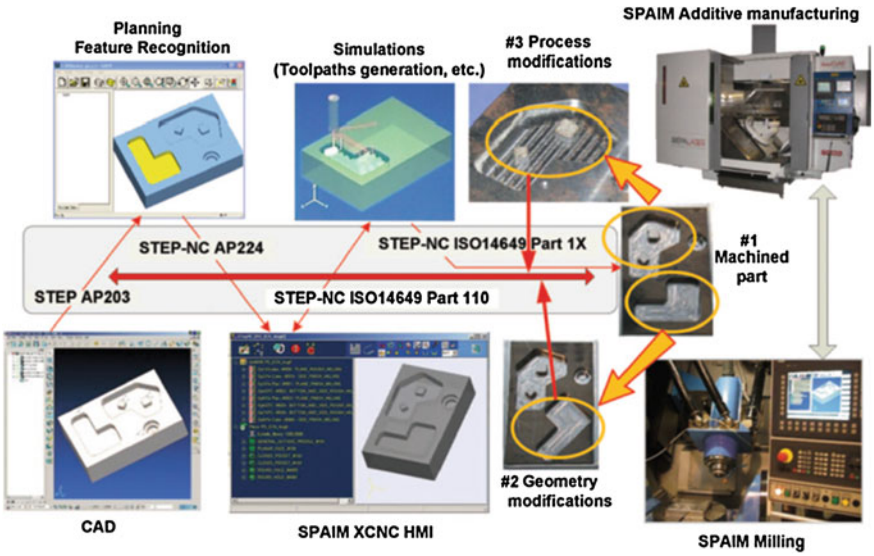

Fig. 9.11 Increasing flexibility through shopfloor modification using STEP-NCSTEP-NC

The manufacture of the first part, the Fishhead shown in Fig. 9.10, is straightforward: 3-axis milling for roughing operations followed by 5-axis finishing operations. Using SPAIM, the manufacture of this part is completely flexible and adaptable to the current conditions on the shopfloor. This flexibility involves the following scenarios: (1) a required cutting tool is not available, damaged or broken. Solution: the operator finds a suitable replacement of similar characteristics but of a different size, he or she modifies the associated tool or adds a new one to the STEP-NC data; (2) an expert operator at the shopfloor recommends a last-minute modification to a particular milling strategy due to changed clamping locations, part reorientation, tool chatter etc. Solution: operator modifies the associated strategies in the STEP-NC data.

For each of these scenarios and modifications, the STEP-NC data is updated and the modifications archived for traceability. The new data is fed back to CAD/CAM/simulation modules to accommodate changes, the updates are then simulated, and new explicit toolpaths are generated for execution. All these activities are performed without leaving the machine's HMI. Each of these scenarios were not originally envisioned in the process planning stage but are completely supported with the multidirectional STEP-NC programming.

In a series production environment, this flexibility is useful for the manufacture and qualification of the first parts used to validate the process. After the validation and the start of production, the ability to quickly and easily switch between similar CNC machines becomes very useful again since STEP-NC is not machine-specific.

The necessary modules used by SPAIM would be available within the CNC CPU environment. The advantage would therefore be seen through increasing production agility, reducing downtimes and delays as well as improving macro process planning around damaged machines for example.

For non-series production, these benefits of flexibility and adaptability are equally applicable, even essential, since variability and process/production demands could be more significant. This would therefore necessitate high production agility to meet these demands.

The manufacture of the second part, the pockets with bosses shown in Fig. 9.11, is also straightforward: pocket milling with an appropriate strategy to accommodate the bosses. The true power of STEP-NC is evident and essential when one considers the increased ability of a shopfloor or factory to adapt and optimize their operation even as scheduling priorities and machine maintenance occur. This second test part emphasizes how optimization and last-minute modifications could enhance flexibility and adaptation to current shopfloor conditions [25].

The steps and computation necessary to manufacture this part with SPAIM is shown in Fig. 9.11. From the part CAD model, the feature recognition module is executed and the generic STEP-NC data are created. For each feature, the manufacturing process parameters are selected according to the operator assisted by process simulation tools. An initial part (#1) was directly machined from the input of STEP-NC data into SPAIM. This initial part, conventionally machined, serves as a reference to which flexibility possibilities would be judged.

Using SPAIM's HMI, several tests were conducted with part geometry and machining parameters modifications directly on the machine on the shopfloor. As an added benefit, such modifications are not only limited to the shopfloor. Direct modification can also be attained from distributed and distant computers that share the SPAIM application modules. Two examples of modifications are presented in Fig. 9.11, the first deals with geometry changes and the second deals with manufacturing process change. For the first modified part, a rotation of a feature was performed (#2) showing possible geometry modifications on the shopfloor or at the final stages of production process planning. The new data is recorded and feedback to CAD and simulation modules thus taking into account the modified data. The toolpath generation module updates the strategies and the part is re-machined. For the second modified part (#3), the manufacturing operation to produce the two bosses was changed from milling to additive manufacturing (elaborated in Sect. 9.4.4). The platform, which is distributed on both milling and additive manufacturing machines tools, carried out the required operations automatically: toolpath generation, validation and control. A feedback to macro process planning data in CAD and inter-process simulation is also concurrently enabled from the modified STEP-NC data before re-machining the part. Such scenarios are common place in manufacturing and following the old G-code paradigm shown in Fig. 9.1 would require going back up the numerical chain to isolated CAD/CAM environments and making the necessary modifications. The resulting changes would then be transferred to the CNC after post processing, all of which are time-consuming activities. With STEP-NC and the SPAIM application, the constant feedback and dialogue between the associate systems means that the previous limitations can be circumvented resulting in unparalleled flexibility and a work lose?: coming. The range of this application is certainly not limited to the milling process as already explained but it could be adapted to numerous other processes as well. As manufacturing conditions constantly change, higher level systems such as Process Planning can also benefit by the increased agility of the shopfloor and new optimized non-linear planning can be established as a result of this capability.

The illustration with the Fishhead and the ‘Pockets with bosses’ parts serve to emphasize how current industrial CNC machines can exploit the Indirect and Interpreted levels of STEP-NC. Manufacturers will instantly see increased flexibility and agility as they are able to modify part geometry, machining parameters, and even optimize processes and production with direct input from the shopfloor. With the constantly changing manufacturing conditions, manufacturers are searching for ways to be even more agile and flexible. These inherent benefits of STEP-NC directly provide a solution to meet these higher demands of the factory and the ubiquitous machine-tools that support it.

To understand how these capabilities can be obtained by manufacturers, a list of necessary components is detailed in Sect. 9.7. Manufacturers are encouraged also to visit the IRCCyN laboratories in France for a first-hand look and demonstrations.

9.4 Advanced and Future Possibilities with STEP-NC

The many benefits of STEP-NC and the applications to exploit it are well documented as described above. The capability for higher flexibility and agility in a single process is unparalleled using STEP-NC and they serve as a way to allow the manufacturing industry to migrate to the STEP-NC framework in a step by step manner. However, from the Authors point of view, despite these very useful capabilities, it is the scarcely explored future possibilities of the STEP-NC paradigm that are even more important and in need of serious attention. These possibilities understandably represent a shift in the mindset of the manufacturing industry and the adoption of a different method of system interaction. This section elaborates on these possibilities that are seen as the next frontier in the evolution of manufacturing methods. The following topics are discussed:

1. Interoperability through hybrid manufacturing environments
2. Improved manufacturing supervision and traceability
3. Flexibility and efficiency with high knowledge and information transfer
4. Production optimization and simulation in multi-process manufacturing.

9.4.1 STEP-NC in: Manufacturing Interoperability

It known that in the current global context, a major problem lies in data portability between systems in a manufacturing data chain that is often distributed [10].

The ability of STEP-NC to support intelligent NC programming applications has been explained and demonstrated. It offers a vendor-neutral solution with numerous opportunities for improving manufacturing cohesiveness and production collaboration. A general consensus is that STEP-NC can stand as a valid solution to respond to current portability and interoperability needs. Numerous research projects have proposed and elaborated this idea: the Universal Manufacturing Platform developed at the University of Bath [23] and the UbiDM (Design and Manufacture via Ubiquitous Computing Technology) of Pohang University of Technology [24]. Despite current implementations of STEP-NC being limited to research and feasibility demonstrations, they represent a solid foundation for future developments that will be used to persuade the manufacturing industry and break the current roadblocks to wider adoption.

9.4.1.1 SPAIM + IIMP

Extending the capabilities of STEP-NC as an interoperable solution, two manufacturing platforms (SPAIM and the IIMP project from the University of Auckland) can be seen to fill this role adequately, either separately or integrated.

The framework of SPAIM, already explained, bridges the barrier between the typical systems used in the manufacturing numerical chain (CAD-CAM-CNC) with a particular focus at the shopfloor. Enabling interoperability amongst these systems, SPAIM represents a comprehensive STEP-NC multi-process supervision platform (Fig. 9.9).

Another system that has similar capabilities is the Intelligent and Interoperable Manufacturing Platform (IIMP) [26]. This system augments the capabilities of SPAIM by extending manufacturing efficiency and interoperability. Data portability between the heterogeneous proprietary formats of CAD/CAM/CNC systems and process interoperability is also realized in the IIMP. Although IIMP and SPAIM can be implemented individually, they collectively form a complete framework that covers the whole manufacturing data chain. By interacting with every link, this framework improves supervision and integration of the machining systems (Fig. 9.12).

The focus of the IIMP is to foster a collaborative environment among existing and future CAD/CAM/CNC systems. It relies on the high level information in STEP-NC to make interoperable links between the associated systems within the manufacturing data chain. Like SPAIM, it keeps commercial CAD/CAM/CNC data and software as vital well-established knowledge and information sources. IIMP does not try to link all systems and their data perfectly but provides a mechanism via STEP-NC that allows it to convey only the small subset of

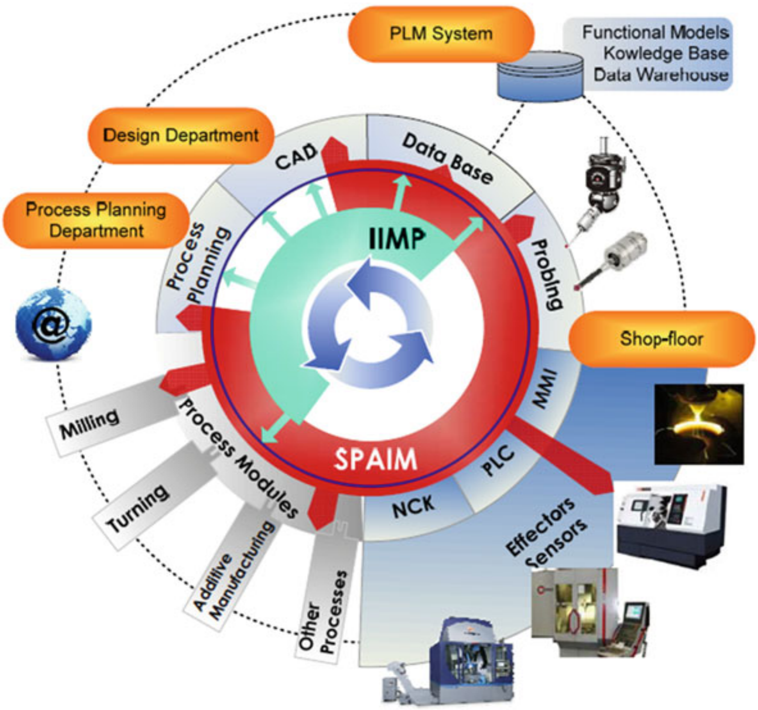

Fig. 9.12 Complementarities of SPAIM and IIMP in for advanced CNC manufacturing

accurately defined data between systems. This allows homogeneity at the platform level compared to the heterogeneity amongst the associated systems.

IIMP Architecture

The architecture of the IIMP is composed of three main element groups: an orchestrator, an application module pool and an execution core (Fig. 9.13).

The orchestrator's role, the main decision center of the platform, is to act as the main HMI. It get user requests, generate a roadmap of their project and control information flow between modules and the execution core via the event-driven supervisor. Due to this central role, the orchestrator's capabilities directly impact the platform's efficiency. The roadmap generator has a direct link to the application module pool and it is used to translate the user's request into a list of events and tasks that each application modules will perform in a predefined order. To fulfill the user's request, the previously defined roadmap is followed. Template scenarios and roadmaps also exist as a way to transfer knowledge from previous requests and to optimize execution of repeated tasks and projects.

With the roadmap generated, the event-driven supervisor calls the application modules according to the roadmap and the resulting information is stored in the

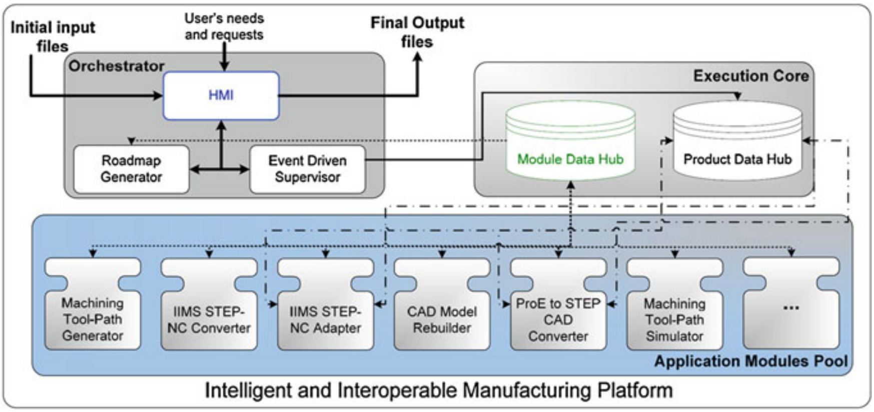

Fig. 9.13 Overview of the intelligent and interoperable manufacturing platform

execution core. The supervisor controls the information flow within the platform modules and the product data hub of the execution core. The execution core is responsible for run-time data exchange and storage by utilizing two hubs. The module data hub focuses on the application module pool and it stores all relevant data for the orchestrator to generate the roadmap and control the information flow during the process. The product data hub manages internal information during project execution. The application module pool consists of different standalone modules that perform specific tasks as directed by the supervisor, including toolpath generator, CAD file converter, CAM functions etc.

Two key features of this platform are flexibility and robustness which are obtainable though its modular design. It was designed to encapsulate existing software tools with an event-and data-driven layer used to control their input and output data. This results in no internal interactions between the modules and there is no restriction concerning the number and the nature of the modules [9]. The design (Fig. 9.14) follows the function block concept of the IEC-61499 standard for distributing industrial-process measurement and control systems [27].

The primary goal of the IIMP is to gather and synchronize heterogeneous data from CAD/CAM/CNC systems. It does have some limitations such as significant dependency on the orchestrator's efficiency as well as optimization trade-off for flexibility. However, it does offer a viable solution, complimentary to SPAIM, to the interoperability of distributed manufacturing with STEP-NC.

The issue of interoperability is an important one. It is a key motivation for the proposal of hybrid manufacturing environments, such as these, which are able to make existing software systems cohabitate with the new STEP-NC programming approaches. This allows continual development and permits step by step migration into the STEP-NC framework. Building on the knowledge obtained in implementing these systems represents a strong resource for future developments.

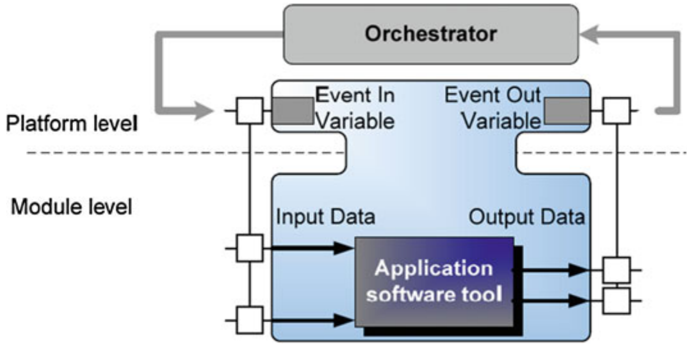

Fig. 9.14 Function Block concept for the application module pool

9.4.2 SPAIM + XMIS in a Digital Factory

Going even farther beyond the interoperability capabilities of the process-focused standard SPAIM and IIMP frameworks, in 2011, Laguionie et al. proposed the extension of STEP-NC from the process manufacturing-level to the higher enterprise-level systems so that a complete integration of the enterprise numerical chain could be possible [25]. This would see the integration of applications from enterprise level (PLM, Enterprise Resource Planning (ERP), etc.), plant level (Manufacturing Execution System, Quality, Control, etc.) and low-level process automation and controls (NC programming, monitoring, inspection, etc.). They proposed an eXtended Manufacturing Integrated System (XMIS) for feature-based manufacturing with STEP-NC, integrating information from design to manufacture.

XMIS Architecture

The goal of the XMIS is to control the manufacturing process from design to product, by integrating Manufacturing Engineering, Manufacturing Quality and Validations and Manufacturing Production data (Fig. 9.15). XMIS is based on several units managed by a Production Project Unit (PPU). A multi-directional collaboration between the units allows their integration in an extended manufacturing numerical system. Feedback from each layer of manufacturing is enabled for experience capitalization, process optimizations and process planning. It is consequently adaptable to the specific needs and evolutions of the company.

XMIS is composed of the following main units:

Production Project Unit (*PPU*) Stores and manages high-level project data for production. It makes the link with the PLM platform by including Design and Development, Analyst, Prototyping, Marketing, Service and Support, Supplying, Sales, etc. Relevant information is shared not only with different services within the company but also with external actors (manufacturing partners, customers, etc.). A main goal of the PPU is to control the visibility of data. While its objective is to convey the right information to the right place for a specific need.

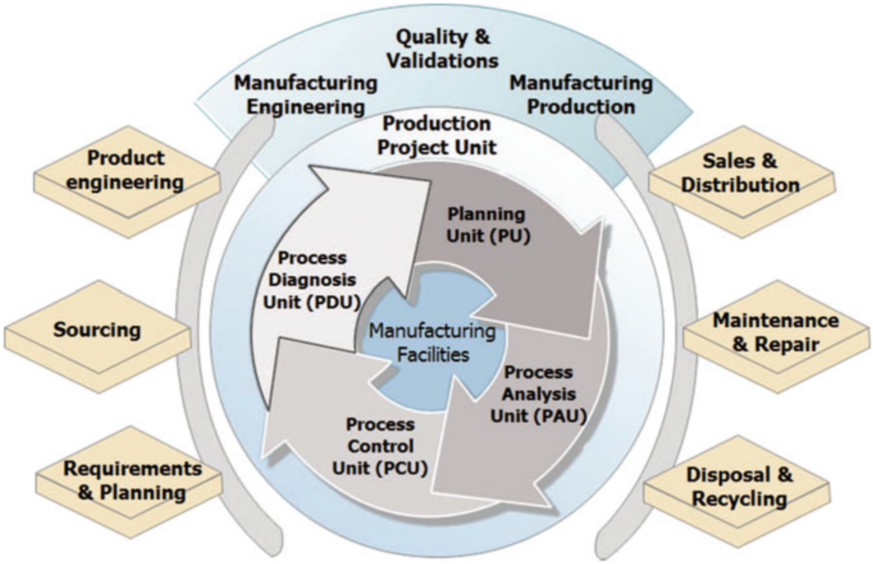

Fig. 9.15 The XMIS in a PLM environment

Planning Unit (PU) Treats the CAD model of a part for process planning. Several aspects are considered by linking with PPU. Manufacturing workplan and features are selected according to available processes, facilities, resources and manufacturing partners.

Process Analysis Unit (PAU) Runs part manufacturing simulation, optimization and verification. This includes operation sequencing, tool and machining conditions choices, toolpath (TP) generation, etc. This unit is linked with the manufacturing data warehouse and the manufacturing knowledge database in a bidirectional way. Such a link allows for the inherent benefit of optimization from experience and experience capitalization of the best solutions.

Process Control Unit (PCU) Executes process online control and monitoring. It performs online compensations, optimizations, diagnosis and adaptive control. Depending on the company structure, this unit can share applications at shopfloor level, on manufacturing facilities level and at production management level.

Process Diagnosis Unit (PDU) Runs measuring and analysis tools for part conformance, production quality and validation. It includes machining post-diagnosis and corrections. Shopfloor experience capitalization can be implemented and a feedback to other units is allowed, thanks to the Manufacturing Information Pipeline (MIP) directly linked with the PPU.

Each of these main units make up the XMIS and they each gather tools and modules that have to communicate together using industrial information and communication standards. The communication standards supported by XMIS are selected to facilitate interoperability. Consequently, to their limited range, propriety vendor-specific pseudo-standards are used in a limited way when necessary.

Open communication standards such as XML and MTConnect are used to facilitate reliable communication and interconnectability between heterogeneous hardware and software applications. Meanwhile, the case to extensively use the STEP-NC data model in XMIS is an important consideration. Although it is a relatively young standard and in need of further development and implementation, STEP-NC represents a compromise that bridges the gap between specific and generic manufacturing data. It covers a very large range of manufacturing data to suite different environments while at the same time enabling data feedback from the shopfloor to CAx systems.

The STEP standard is also used within XMIS since it offers a unified standard to describe all the aspects of a product during its life cycle. Defined STEP application protocols are dedicated to different application domains from design to maintenance. It is used widely in the industry and integrated in most CAD/CAM systems for design data exchange. The XMIS concept proposes to combine STEP and STEP-NC for internal and external data exchange between modules and units from design to NC and inspection.

Within XMIS, two categories of STEP-NC data are identified: Generic STEP-NC data and Optimized STEP-NC data. These two categories are influenced by the scope (either Macro or Micro Process Planning) in which STEP-NC data is needed. Figure 9.16 describes the necessary inputs and units required to create both the Generic and Optimized STEP-NC data.

In Macro Process Planning (MacroPP), the focus is on process choices based on manufacturing features definition and work planning requirements. Performed by the PU, MacroPP treats parts manufacturing in a multi-process context.

With the help of inter-process and intra-process planning simulation tools in the PU, MacroPP gathers information to create manufacturing operations workplan by using Generic STEP-NC data. In this scope, Generic data only depends on process choices and therefore totally independent from any specific machine-tool or manufacturing equipment.

In Micro Process Planning (MicroPP), all the activities related to particular manufacturing resources and parameters are gathered together. Performed within the PAU with the help of specific intra-process and inter-process simulation tools, MicroPP is linked with the machine-tool functional models (MTFM) of the selected manufacturing facilities. All the information generated is optimized for a manufacturing resource within the PPU and supported by optimized STEP-NC data. Links to other departments of the company can be made and the optimized STEP-NC data can be directly executed on the CNC controller.

XMIS MIP

Facilitating the exchange of information within XMIS is the MIP shown in a 3D representation in Fig. 9.17. The MIP makes a sharp departure from the traditional top–down data flow of the current numerical chain. Instead is uses multi-directional data exchange, supported by standards, enabling data exchange horizontally between modules (Mui) of the units, vertically between the units and radially between all modules and the PPU.

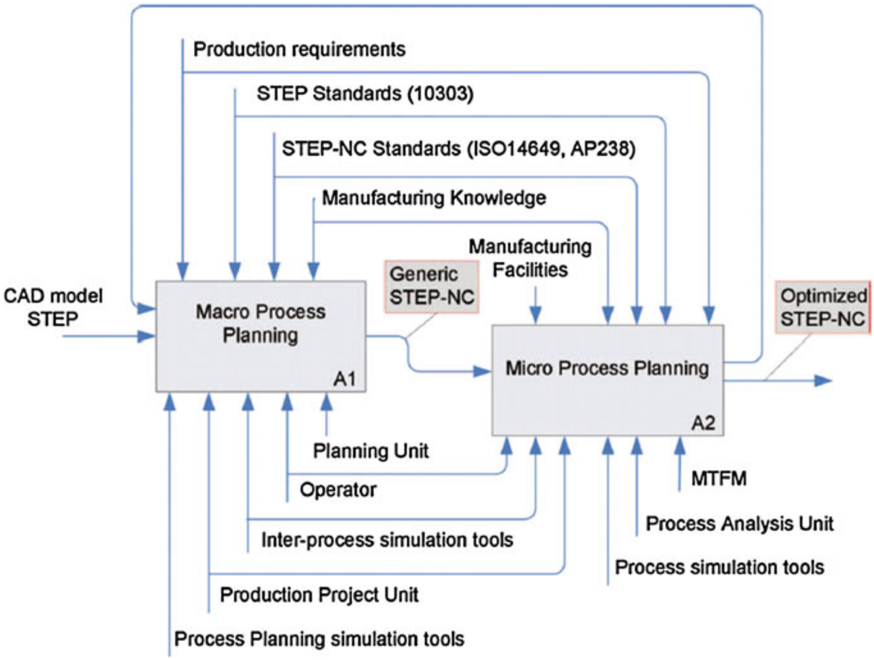

Fig. 9.16 Generic and Optimized STEP-NC data in XMIS

The modules are integrated in the units as ‘plug and play’ while the Unit Interpreter links the computation results of the units with the PPU Databases. Local Unit Databases store the internal unit computation data in the native module standard and can be interpreted in vendor-neutral standards (STEP or STEP-NC) for inter-modules data exchange. The PPU manages databases shared between the different units (Manufacturing Knowledge Warehouse, TP database and MTFM). Data visibility is controlled at the PPU level for units to have access to the relevant information. PPU also manages visibility and security of manufacturing information exchange with all the other stakeholders services of the company (design, sales, supply chain, etc.) and partners (customers, collaborators, etc.). Machining facilities at the shopfloor are totally integrated in the numerical chain.

The MIP supports machining control and monitoring from the PCU. From the STEP-NC-specific data, PCU directly pilots the machining resources using a STEP-NC compliant controller. The use of current industrial controllers is also enabled by adapting TP and machining parameters for specific NC. Quality of the production is measured and validated by the Production Diagnosis Unit. Online and offline inspections are supported by ISO 14649 (Part 16) also called STEP-NC inspection. Sensor feedback from machine-tool to Production Control and Diagnosis Units can be supported by open communication standards. Experience capitalization and data management are allowed from design to machined part.

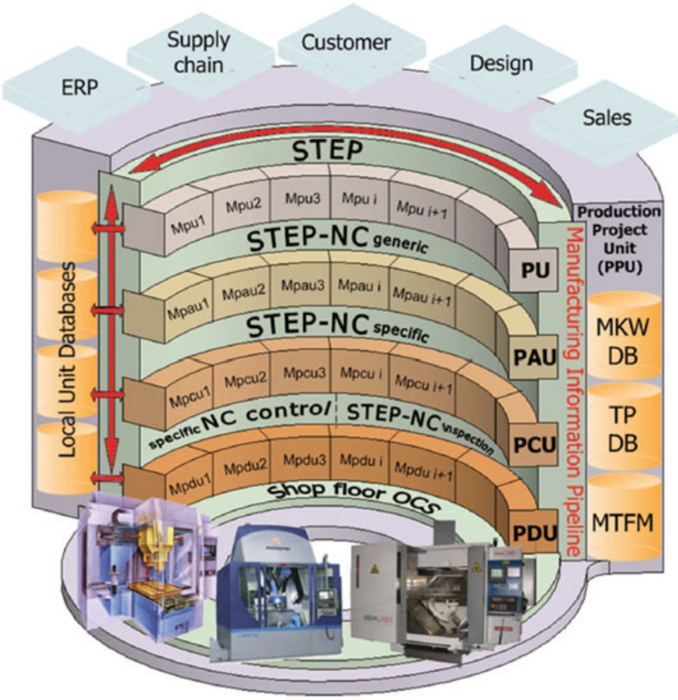

Fig. 9.17 XMIS units and the manufacturing information pipeline

Hence, the MIP supports common standards for improving interoperability at every stage of the manufacturing numerical chain.

Given the structure and architecture of the XMIS units and the MIP, they could be adapted to any enterprise according to their needs, requirements and capabilities. This therefore completely supports the 'Design anywhere, Build anywhere, Support anywhere' paradigm expected of manufacturers today in the evolution of the Digital Factory.

To demonstrate and validate this XMIS concept, the capabilities of the standard SPAIM application was extended (Fig. 9.18). A version exists that demonstrates parts of the XMIS system, tailored to the needs at IRCCyN. Some XMIS units are totally implemented and tested as part of the first demonstrator of the XMIS. Extended CAD (CAD + PU) and CNC (CNC + PDU, PCU, PAU) environments are defined and implemented to encompass milling and AM machines.

The concept of XMIS applied on industrial equipment is promising particularly since its design is modular with multi-directional high-level data exchange. Using both STEP and STEP-NC data to increase the interoperability between different vendors-specific applications will result in significant reduction in the information loss while at the same time improve knowledge capitalization. As technological

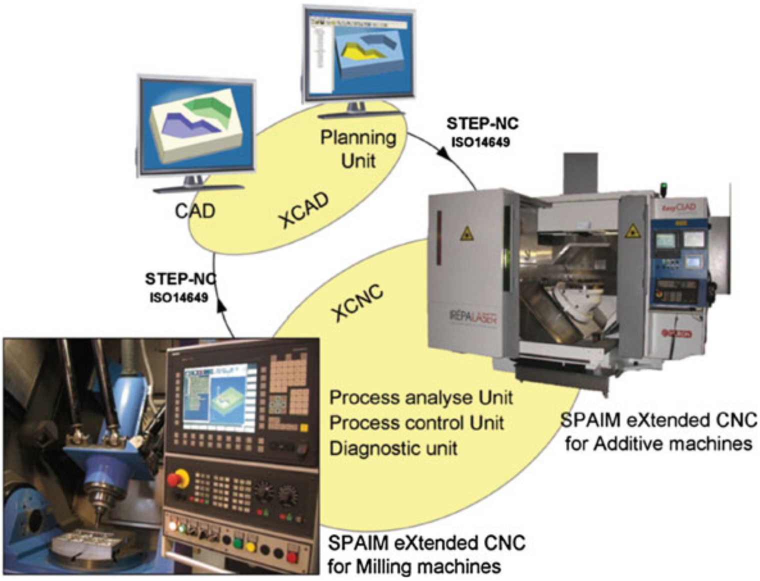

Fig. 9.18 SPAIM in XMIS

capabilities in manufacturing continue to improve, the implementation of XMIS will lead to the realization of feature-based manufacturing with STEP-NC, integrating information from design to manufacture.

9.4.3 STEP-NC in: Open-Architecture CNC (Open-NC)

Within the scope of the FP7 European Commission funded project, FoFdation, the development and extension of the STEP-NC framework into an open architecture CNC has been proposed and developed. Centered around a vision of the Next-Generation self-learning, intelligent and efficient CNC controller, the Consortium defined the FoFdation Smart Machine Controller Open Architecture (FSMC-OA) [28]. The resulting controller prototypes uses currently available tools and new developments to build an Open-NC platform for showcasing CNC functionalities that are expected even demanded, on future CNC machine-tool. It is also a way to adequately showcase the inherent open-ness, portability, scalability and interoperability of new applications and processes (Fig. 9.19).

Efforts within this project have seen the transformation of an industrial CNC (Cincinnati Milacron 'Sabre' milling machine with a NUM controller) into a unique multi-controller Integrated Test Platform (ITP). Alongside the original NUM-750 numeric controller, two separate CNCs have been added: the LinuxCNC (formerly EMC2) open architecture controller and the legacy nC-12 controller from Fidia.

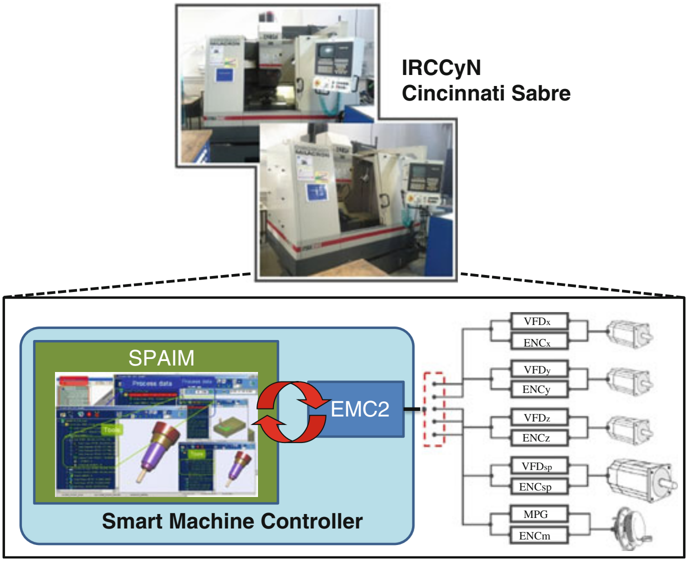

Fig. 9.19 IRCCyN's Sabre machine-tool equipped with the Open-NC controller

They all co-exist within a single machine-tool, sharing the same physical configuration. This implementation allows selecting, via a physical signal switch, which controller actuates the Sabre's axes (spindle, linear machine axes and handwheel).

The ITP was created to realize and demonstrate the evolutionary steps and benefits of STEP-NC. Furthermore, it serves as a unique all-in-one station to concretely illustrate how current legacy CNC controllers can, in the short term, benefit from and eventually migrate to the STEP-NC paradigm in the medium term. It also sets the stage for long term future developments towards the Next-Generation self-learning, intelligent and efficient CNC controllers. Using the three physical controllers mentioned, the ITP can be operated within 4 different CNC controller environments: NUM, LinuxCNC-ISO, LinuxCNC-STEP-NC and Fidia (Fig. 9.20).

NUM: The NUM controller is capable of conventional 3-axis CNC machine control and milling similar to any industrial vertical milling machine. The simple controls and wide use makes this controller a good candidate for conventional milling activities.

LinuxCNC (ISO + STEP-NC) The LinuxCNC controller possesses 2 separate operational modes thanks to its Linux OS and Windows OS on-board computers. It can be used as a conventional ISO-code driven CNC controller providing state-of-the-art 3-axes control for the Sabre's axes using its Linux based real-time kernel. The Windows extension PC means that a host of software from CAD, CAM to algorithms and in-house developed software can be used with this CNC. This is an important point because testing new developments and algorithms is either not possible or difficult to do on propriety CNCs. Therefore having such an

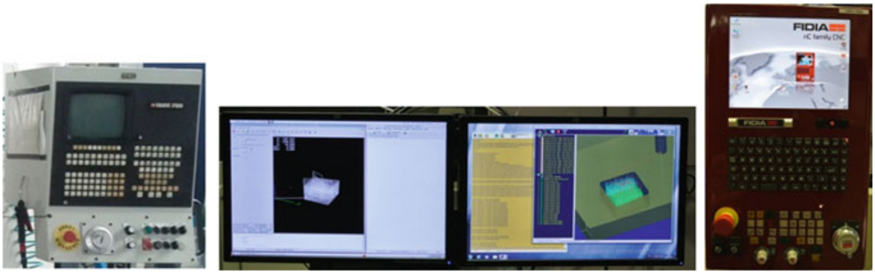

Fig. 9.20 HMIs on ITP: NUM-750, LinuxCNC-ISO, LinuxCNC-STEP-NC and Fidia nC-12

open architecture CNC removes this limiting barrier. The LinuxCNC can also be used as a STEP-NC compliant controller with the addition of the SPAIM platform for advanced STEP-NC programming and control.

Fidia nC-12 CNC The Fidia controller is also a conventional CNC platform based on Windows OS with Fidia-developed servo drives, PLC and other I/O peripheries. It provides state of the art CNC functionalities and advanced control. As it operates within the Windows "de facto" standard environment, implementation of third party software such as CAD/CAM is possible. This fact also makes is a good candidate to demonstrate STEP-NC compliancy again with the addition of the SPAIM platform.

The ITP focuses on addressing 3 main points:

(1) STEP-NC programming evolution in the three levels: Use the unique multi CNC controller environment provided by the ITP to demonstrate the first (Indirect) and second (Interpreted) STEP-NC evolution stages while continuing the evolution of the third stage (Adaptive) in STEP-NC advanced programming.
(2) Real-time process data: Combining the flexibility of STEP-NC provided by SPAIM with algorithms and the ICAM methodology developed for toolpath programming optimization based on real-time process to produce better and more accurate parts.
(3) NC-Interpolation and trajectory planning: Develop smoother and more accurately controlled toolpaths driven by optimization.

The IPT (Fig. 9.21) is seen as an important tangible demonstrator for manufacturers to understand how they can begin to benefit with STEP-NC. It will also serve to show the steps necessary to make a legacy CNC machine-tool STEP-NC compliant. Manufacturers will be encouraged to see and make use of some of the many benefits of STEP-NC today on their existing machine-tools and NC controllers allowing them to realize higher flexibility and process optimization.

Researchers can also benefit from this unique machine-tool with multiple controller environments. It is well known that no two machine-tools or CNC controllers, even from the same manufacturer, perform equally. This makes it difficult to perform substantial comparison between different controllers and

Fig. 9.21 The FoFdation integrated test platform

machines. Therefore, having a single machine configuration with multiple controllers permits a more appropriate comparison that is not hindered by large machine to machine variation. The ITP can allow this to happen and can be used for tests and research activities ranging from comparing machine and controller performance, to STEP-NC developments and milling process optimizations. All of which are underpinned by extending the flexibility and efficiency of manufacturing tools with high knowledge and information transfer.

9.4.4 STEP-NC in: Optimization and Simulation for Multi-process

Optimization

Extending the STEP-NC standard to other processes is an important step in making this paradigm shift widespread. Amongst the existing processes already defined, the ISO 14649 part 13 [29] focuses on wire Electro Discharge Machining (EDM) [30] and other works are done to build a STEP-NC data model for Additive Manufacturing (AM) [31]. By supporting all these different kind of process data, STEP-NC offers the ability to integrate, supervise, link and make interoperable all these processes using a unified integrated manufacturing numerical chain. Each process has its own specificities that result, if following the current G-code numerical chain, in the isolation of their implementation. Information available in G-code files cannot be exploited as it is too low level: only a small quantity of the data linked to the machining process is included. As STEP-NC supports a large field of object-oriented data from CAD to CNC, it allows integrating multiple

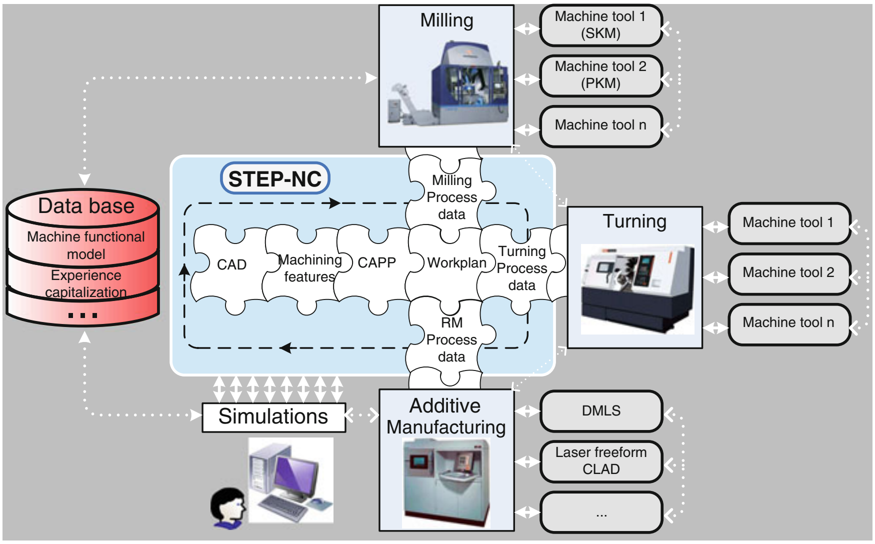

Fig. 9.22 STEP-NC multi-process numerical chain

processes through a common standard for several machining processes. To support such a configuration, the innovative concept described by Fig. 9.9 is essential for comprehensive multi-process supervision. The part model can reflect the modifications and updates concerning every manufacturing process. When process dependencies are necessary, STEP-NC is an appropriate standard to unify, support and link various process data. Whereas the current numerical chain only relies on expert users' practices, STEP-NC offers new possibilities to integrate a comprehensive data support. It opens the way for a strong communication hub between experts by using a common well-adapted language. It would also provide data support for computational simulation and optimization of the multi-process workplan. However, multi-process approach involves more and more complex scenarios (Fig. 9.22) for which large efforts and continued research are needed to developed and validate a totally integrated numerical chain.

With the interaction of multiple processes and experts, decisions can be made not only by considering individual processes but by integrating the requirements of the whole manufacturing numerical chain. This interaction has an implicit benefit of allowing extensive part and process optimization throughout the factory.

Additive Manufacturing

A novel process that lends itself quite nicely to the STEP-NC framework as well as to the multi-process capabilities is Additive Manufacturing. This process has been defined in STEP-NC by researchers at IRCCyN and it opens a new range of manufacturing possibilities. Since material is added instead of removed, compared to other conventional processes, the types and complexity of new part creation that can be produced is greatly increased. Even more useful is the possibility of part and

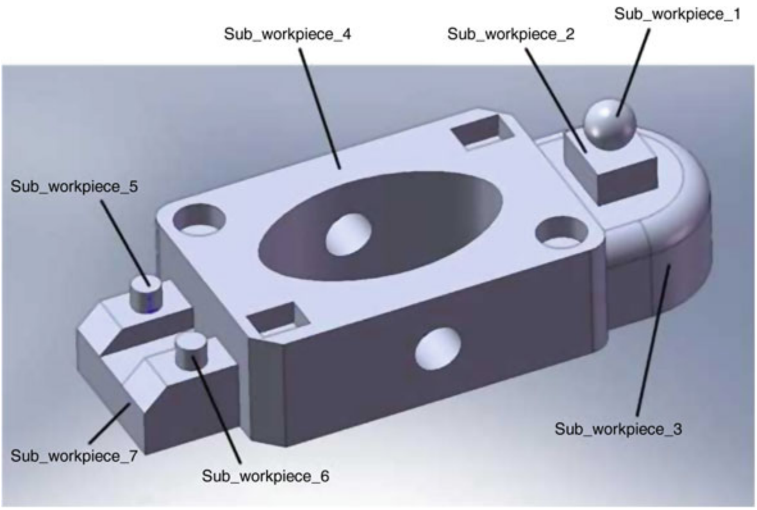

Fig. 9.23 Example part for additive manufacturing

manufacturing hybridization by combining multiple processes (Fig. 9.23). In the figure, multiple features that would have been milled, for example, are redefined as AM sub-workpieces to be created using a multi-process workplan. The main advantage is therefore overall production simplicity. Furthermore, some features, like conformal cooling channels for example, are more easily fabricated with AM than conventional methods, so again production capabilities can be extended. The addition of AM capitalizes from the use and reuse of previously defined manufacturing features for other processes in STEP-NC. For features not currently defined, the researchers proposed the addition of new AM related features. An illustration of this strength of AM in multi-process STEP-NC is shown below.

Experimental Validation Study

To emphasize this idea of optimization (process and production), an experimental study was conducted to validate the efficiency of such a multi-process manufacturing approach. The test part in Fig. 9.24 is used. It is a drawing die for which functional requirements calls for hardened steel at the top of the die.

Although this part is geometrically symmetric and would be more efficient in a turning process, it would need to be machined by milling to accommodate for the pyramidal shape at the top. Further processing such as thermal treatment would be required to fulfill the functional requirement. With the multi-process capability of STEP-NC within the SPAIM application, a different processing scheme presents itself and the results are more efficient in terms of meeting production requirements as well as utilizing each process efficiently. In this new scheme, three manufacturing processes were used: additive manufacturing (CLAD), turning and milling.

Fig. 9.24 Drawing die in multi-process manufacturing

A STEP-NC enabled CNC controller possesses workplans (micro process plan) made of multi-process workingsteps. In this environment, the effectiveness of a multi-process manufacturing application like SPAIM is evident (Fig. 9.24). This scheme presents several situations that multi-process optimization (performance, execution and general) is a natural conclusion and opens up new avenues for production that were once considered too complex or even impossible.

Performance optimization: tailoring production for performance and functional requirements such as strength, surface and hardness characteristics though multi-material parts i.e. adding hardened steel via AM to a different substrate metal.

Execution optimization: creating new possibilities for part fabrication, this optimization allows production execution sequences to be flexible and gives macro and micro process planning more agility. One benefit is being able to decouple manufactured features from any specific process e.g. creating bosses from AM instead of by milling which would have resulted in excessive material waste. This optimization opens a whole new direction in the way parts are produced, especially in the advent of novel fabrication methods like AM.

General optimization: reducing manufacturing difficulty and complexity by splitting or distributing production to other specialized processes. An example is combining turning and AM instead of straight milling as was done with the drawing die test part.

The manufacture of this drawing die, for example, satisfies all three optimizations at once: simplicity, tailoring and flexibility. With a conventional manufacture of this part, there is little cohesion between the part and the processes used to fabricate it. This means that if multiple processes were used to manufacture this part without STEP-NC, each associated process would have its individual process execution plan and they would be totally independent of each other. This lack of cohesion makes is very difficult to share information and knowledge between the experts and the processes. However, in STEP-NC, there are very cohesive links which are magnified and allow more holistic and optimized part production. There is a single process plan even for the multi-process manufacture of this part. Features that are not involved in a particular process can be 'frozen' or hidden from view and 'unfrozen' when needed. Knowledge is shared between processes in this case which leads to improved optimization execution. Although the added extra process could be considered an increase in complexity or production time, the benefits of being able to create a unique multi-material component for targeted applications outweighs those concerns depending on the sector.

Briefly explained in Sect. 9.3.1, multi-process optimization was also applied to the manufacture of the simple part with pockets shown in Fig. 9.11. In this case, the relative manufacturing difficulty is reduced by extending production to multiple processes, each with their own inherent advantages: straight pocket milling with simpler toolpath for area clearance and AM to add the bosses using similar or different materials compared to the base substrate material.

Embracing STEP-NC in a multi-process environment has significant advantages especially in the new possibilities it creates for part fabrication. Sharing information between processes leads to performance, execution and overall optimizations that are difficult or impossible to achieve by conventional methods.

Simulation

In order to progress the advance possibilities of STEP-NC use, Laguionie et al. defined a proposal on how simulation could be approached in a multi-process environment [22]. Three main simulation spaces (Fig. 9.25) are identified and defined as well as their interaction zones. A simulation space is defined as a boundless but structured set where simulations can be performed. The figure shows schematized imaginary boundaries representing knowledge limits however the boundaries can be infinitely extended. These simulation spaces can be distinguished by their respective objectives. They are complementary, interdependent and closely linked.

The main input of the manufacturing numerical chain is the CAD model of the part. This CAD model contains data for part geometry, tolerances, material, etc. These characteristics must be respected and are a theoretical objective for manufacturing process. However, every process has its own constraints that must be taken into account when deciding the manufacturing workplan of the part.

Main Simulation Space

(1) From CAD to manufacturing features and process plan: the Multi-process planning simulation space (Empp)

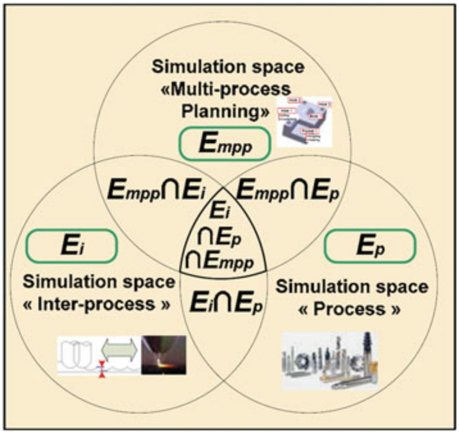

Fig. 9.25 Simulation in a multi-process environment

Discretizing a CAD model into manufacturing features means more than recognizing usual geometrical entities. A lot of research works have been done on manufacturing feature extraction [32]. It appears that the solution can hardly be separated from the manufacturing process involved. In other words, the choice of manufacturing feature geometry is linked to a process. Thus, a simple part can lead to several feature decompositions depending on the process choice in a multi-process environment, as the process is not fixed. In some cases, indecision of a suitable process to machine a particular feature can lead to further simulations. This is the exploration field for the *Empp* which objective is to find the optimal machining features and process plan.

(2) Process simulation space (Ep)

The workplan is composed of several workingsteps associated with the manufacturing features. The process simulation space (*Ep*) gathers all the computations and choices concerning process data and machining parameters selection. *Ep* is involved for high level manufacturing data selection in STEP-NC but also integrates shopfloor simulation in the interpreter. This shopfloor simulation can be performed offline or online. Typically, an offline simulation will be privileged in the STEP-NC interpreter for tool paths programming, tool paths optimizations, machining parameters adaptation, etc. Real time optimizations, simulations from sensors feedback in the CNC could also be done online and are part of *Ep*.

(3) Inter-process simulation space (Ei)

Relations between processes take a central position in a totally integrated multi-process context. The Inter-process relationship and optimizations are fully integrated in the numerical chain and are a large consideration of the *Ei* space, which is new here. In the traditional G-code based numerical chain, a large part of the simulations concern the process (*Ep*), manufacturing experts choose the well adapted workplan based on their experience and knowledge (*Empp*), but inter-process simulation (*Ei*) is hardly possible due to different data standards and expert communication languages. In the STEP-NC numerical chain, *Ei* is the missing link between *Empp* and *Ep* when several processes are required. Relationship and communication channels between the different processes are enabled with a direct effect on the machining features, the workplan and the process data.

Interactions and Optimized Solutions

(1) Process and process planning interaction

The intersection between *Empp* and *Ep* spaces is the place for process simulations in close link with process planning, and reciprocally. *Empp*∩*Ep* includes the bidirectional relationship between CAPP and each selected process. The relationship between machining entities and process parameters are important. For example, in pocket milling, the tool diameter is limited by the corner radius for finishing operations. Similarly, characteristics of a process can also lead to the selection of a feature over another. For instance, using a step drill to drill a hole and the associated counter bore results in forcing the two features to be merged in one workingstep.

(2) Process planning and inter-process relations interaction

The constraints of each process must be taken into account when creating machining features and workplan. These interactions are simulated in *Ep*∩*Ei*. For example, the thermal effects of Direct Laser Manufacturing (DLM) with powder injection [33] constrain the selected features to be manufactured very early in the workplan, before the finishing operations of high speed milling. Conversely, machining features sometimes constrain the choice of the process sequence and consequently of the inter-process relations. For example, if a flat section must be milled after a turning operation, inter-process interactions are ordered by process planning.

(3) Process and inter-process interaction

The process simulation space *Ep*, directly linked with the machine-tool functional model, can provide the simulation results associated with a selected process. The results can have consequences on the other processes machining parameters. For example, the finishing cutting conditions in a milling process (feedrate, cutting speed, etc.) can be adapted due to thermal effects after DLM machining a feature. A multidirectional data exchange enables a workingstep associated with a process to be performed in an intelligent multi-process context.

(4) A global, optimized solution in the comprehensive Empp∩Ep∩Ei space

The goal to reach is the simulation of a totally integrated manufacturing environment that considers at the same time, relevant multi-process planning, inter-process relationships and process attributes simulations. However, simulation in *Empp*∩*Ep*∩*Ei* involves complex reasoning and simulation methods. Processing the three presented simulation spaces at the same time is certainly not the best way to initiate a solution. Future technological advances could allow this.

The main emphasis here is that with the different simulation spaces identified, this provides a roadmap on which the different experts along the numerical chain can rely to help them make choices, again not only by considering their specific area but by considering and integrating the requirements of the whole manufacturing numerical chain. It also allows STEP-NC developers to have complex situations that they must create solutions for. This is a challenge and one that should be developed further by exploring the limits of the STEP-NC data exchange standard supporting multi-process planning and process data.

9.5 Discussion

One aspect of STEP-NC that is often overlooked is how to enter into the STEP-NC paradigm in the first place. Usually the entry point is a CAD part file supported with manufacturing and resource information. Starting from this CAD part file, the conversion to STEP-NC is currently a semi-automatic activity. Due to the feature-based design of STEP-NC, there is an inherent need to be able to recognize the features described. With the help of manufacturing feature recognition, based on ISO 10303-AP224, some software systems have been developed to extract features using CAD input files (e.g. STEP or parasolids files) [34]. The process is currently semi-automatic because some features like holes are regular enough that they could be extracted automatically. However for more complex features (even some types of pockets or slots), a higher level of human interaction is required to identify those features. The variability of opinion about features within manufacturing and the ambiguous nature of some features make it very difficult to have complete automation. At present, no system exists that is capable of autonomous feature recognition of manufacturing features. Part of the problem has to do with the fact that not all manufacturing features are standardized and not all of the intent behind the design of such features is transmittable without human interaction/input. Even when the design intent could be transmitted, that does not always provide useful information for manufacturing.

For simple features like pockets and holes, SPAIM as a STEP-NC enabled application uses its bidirectional link with CAD to be able to create a part for manufacture directly in STEP-NC format on the HMI. This method is similar to the wizard-like capability of some industrial CNC machines that allow 'Conversational or Shopfloor Programming' via software embedded on the controller's computer. The extent of this method is currently limited but represents another starting point to enter the STEP-NC world.

It should be emphasized that the adoption of STEP-NC does not mean that the current seemingly isolated departments (design, planning etc.) of an enterprise will remain isolated or become obsolete. The exact opposite is true. Adopting STEP-NC necessitates and facilitates the integration of these departments. The full flexibility and optimization capabilities offered by STEP-NC are in fact realizable with such integration. The bidirectional data flow between systems in the STEP-NC numerical chain is not limited only to the systems. The experts that are behind those systems for designing, planning, programming and operating etc. are equally essential. They make up a substantial knowledge source that process and multi-process optimization relies on.

Therefore, the need for human knowledge and experiences in the STEP-NC numerical chain should not be diminished or overlooked. Although many aspects can be automated such as rules-based tools for simulation, cutting tool and machining parameters selection, the need for human experience to optimize process planning for example is essential. Decision making about what strategies are available to manufacture a particular feature, the type of supporting manufacturing resources available are all essential aspects for which a human STEP-NC programmer is currently required.

To develop such a capacity, the programmer(s) is required to have substantial knowledge about manufacturing systems not only limited to CAM or CNC. Current CAD/CAM/CNC programmers and operators collectively already possess the requisite knowledge base. The challenge is to teach them how to think in the non-linear manner that is required by STEP-NC and its applications. This step is not unlike any training to learn and use new machines or software systems.

The leap forward is not as substantial as is often expected and one of the opportunities for the promoters of STEP-NC (the Authors included) is to be able to effectively communicate this both in print and with tangible demonstrations.

It should not be forgotten that STEP-NC and the framework, described in this chapter, are adaptable. Depending on the needs and capabilities of an enterprise, the extent of STEP-NC use and control can be scaled. In a serial production environment for example, the need for shopfloor modifications during production execution is extremely limited and could be completely removed as a capability. In this case, experts would not be required directly on the shopfloor to manipulate STEP-NC but they are expected at higher levels such as planning and validation. Considering this, the cohesive link that STEP-NC enables for systems in the numerical chain (design, planning and eventual optimization of the manufacturing process) can be performed with the efficient use of enterprise resources.

In a non-serial production environment, the needs would again change depending on the capabilities of the enterprise. The conclusion is however still the same: only the aspects of STEP-NC that provide direct benefits and added-value to an enterprise would be used. The very large range of manufacturing data within STEP-NC can be totally tailored to suite different environments.

9.6 Future Focus

For the future, several areas including the advanced possibilities with STEP-NC discussed in this chapter, will require continued development and implementation. Some areas of focus should include:

- improving the capacity of current systems by making them more comprehensive, automated and autonomous.
- implementing and validating the advanced possibilities discussed, particularly the interoperability aspects.
- defining and creating studies that highlight the economic impact as well as quantitative advantages of STEP-NC and STEP-NC systems.
- properly defining industrial needs and qualitative objectives for manufacturing programming.
- consideration of the human element in STEP-NC particularly as it relates to enabling modifications and optimizations as well as improving decision-making and validation at every step of a project.

For all of this to happen, the promoters of STEP-NC will be required to effectively and convincingly communicate positive results to the industry by providing more tangible industry-related demonstrations. Only with sufficient and diverse support from both industrial and academic will this future of advance manufacturing with STEP-NC be realized.

9.7 Adopting STEP-NC (Q&A)

One very important question that is often asked is "What is needed in terms of software and hardware for an enterprise to migrate a machine to STEP-NC?"

As a first prototype used to demonstrate the STEP-NC paradigm, the development of SPAIM required a few constraints. The most important of these is software, which coincidently are currently used in the conventional CAD-CAM chain.

For the moment, if an enterprise wants to adopt STEP-NC based on the SPAIM application, the following items will be needed:

- CAD software: Delcam PowerShape
- CAM software: Delcam PowerMill (with post processor: Delcam DuctPost)
- and of course, STEP-NC programming and training support from IRCCyN.

Initially SPAIM was implemented only on a Siemens 840D controller, however with continued development, it has been implemented on other controllers.

The benefits highlighted in this chapter are currently available through SPAIM on the following legacy CNC controllers: Siemens 840D, Num 750, Fidia nC-12, and Heidenhain. They are also available on the Open-NC LinuxCNC-based open architecture controller. For all the legacy controllers mentioned, no hardware modification is required which makes implementation a quick process. This is a positive point for easing manufacturers concerns about implementation time.

Question and Answer

Q: Could other CAD/CAM systems be used with SPAIM?
A: Currently, no since SPAIM was initially developed using Delcam products. It is by no means limited to those products however. To be able to use other CAD/CAM software systems with SPAIM, more development effort would be required to make the adaptation and automation links.
Q: Could any machine's CNC be made STEP-NC compatible?
A: Yes. Currently available on 4 major legacy industrial CNCs.
Q: Could an old machine-tool be hardware-upgraded or retrofitted and be made STEP-NC compliant?
A: Yes. Having performed an upgrade of the 3-axis Sabre machine-tool by adding LinuxCNC and Fidia controllers for example, the know-how, components and efforts necessary for this adaptation are known and available to be used for future implementations. The addition of SPAIM will allow it to be STEP-NC enabled.

9.8 Conclusions

The benefits of STEP-NC and the applications that support it have been discussed. There are many opportunities for the manufacturing industry to adopt the paradigm shift however continued demonstrations and industry targeted use cases will still need to continue to facilitate a step by step migration to the cohesive possibilities offered by STEP-NC.

With more implementation and validation of complex, integrated manufacturing environments with STEP-NC, the manufacturing industry will be capably of realizing the following benefits: interoperability through hybrid manufacturing environments, improved manufacturing supervision and traceability, flexibility and efficiency with high knowledge and information transfer as well as production optimization and simulation in multi-process manufacturing. All of these benefits will increase systems interoperability and portability, production efficiency and above all flexibility and agility within an enterprise.

Currently, STEP-NC and its implemented applications are advanced enough to allow current industrial CNCs to quickly be made STEP-NC compatible with the addition of the SPAIM application for example. Immediately, they will be capable of Indirect or Interpreted STEP-NC programming and benefit with flexibility and agility. Manufacturers will be able to make modifications to toolpath and strategies, part geometry, tools selection, process plans, optimize individual processes and realize new capabilities with multi-process, all with direct links to the shop-floor. This is undeniably a beneficial capability as manufacturers struggle to meet the demands of a quickly changing competitive industry. STEP-NC at its current state will allow them to be as adaptive and agile as possible as they plan, optimize and react to the conditions on the shopfloor. Additionally, the future potential of STEP-NC enabled manufacturing is promising and more than capable of addressing the eventual needs that will arise.

References

1. ISO_6983-1(1982) Numerical control of machines—Program format and definition of address words—Part 1: data format for positioning, line motion and contouring control systems. In: International Standard Organization
2. Pratt MJ (2001) Introduction to ISO 10303—the STEP standard for product data exchange. J Comput Inf Sci Eng 1:102–103
3. Newman ST, Nassehi A, Xu XW, Rosso RSU Jr, Wang L, Yusof Y et al (2008) Strategic advantages of interoperability for global manufacturing using CNC technology. Robot Comput Integr Manuf 24:699–708
4. ISO_14649-10 (2004) ISO 14649 part 10—international standard organization. Industrial automation systems and integration—physical device control—data model for computerized numerical controllers—part 10, general process data. ISO TC 184/SC1/WG7/FDIS
5. Weck M, Wolf J, Kiritsis D (2001) The STEP compliant NC programming interface evaluation and improvements on the modern interface. In: IMS project forum. Verita, Ascona
6. STEP Tools, ST-Machine STEP-NC for CAM-CNC
7. Newman ST, Allen RD, Rosso JRSU (2003) CAD/CAM solutions for STEP-compliant CNC manufacture. Int J Comput Integr Manuf 16:590
8. Wang H, Xu X, Tedford JD (2007) An adaptable CNC system based on STEP-NC and function blocks. Int J Prod Res 45:3809–3829
9. Minhat M, Vyatkin V, Xu X, Wong S, Al-Bayaa Z (2009) A novel open CNC architecture based on STEP-NC data model and IEC 61499 function blocks. Robot Comput Integr Manuf 25:560–569
10. Suh SH, Lee BE, Chung DH, Cheon SU (2003) Architecture and implementation of a shop-floor programming system for STEP-compliant CNC. C-A Design 35:1069–1083
11. Xu XW (2006) Realization of STEP-NC enabled machining. Robot Comput Integr Manuf 22:144–153
12. Shin S-J, Suh S-H, Stroud I (2007) Reincarnation of G-code based part programs into STEP-NC for turning applications. Comput Aided Des 39:1–16
13. Xu L (2009) STEP-NC in support of machining process optimization. In: Xu X, Nee AYC (eds) Advanced design and manufacturing based on STEP. Springer, London, pp 169–196
14. Ridwan F, Xu X, Liu G (2012) A framework for machining optimization based on STEP-NC. J Intell Manuf 23(3):423–441
15. Kumar S, Nassehi A, Newman ST, Allen RD, Tiwari MK (2007) Process control in CNC manufacturing for discrete components: a STEP-NC compliant framework. Robot Comput Integr Manuf 23(6):667–676
16. Martin YS, Gimenez M, Rauch M, Hascoet JY (2006) VERNE—a new 5-axes hybrid architecture machining centre. 5th Chemnitzer Parallelkinematik Seminar. Chemnitz (Germany), April 25–26, pp 657–676
17. Delcam. PowerSHAPE—CAD Design and Modelling Software. http://www.powershape.com. Accessed 2008
18. Delcam. PowerMILL—Your Total Manufacturing Solution. www.powermill.com. Accessed 2008
19. Dugas A, Lee JJ, Terrier M, Hascoet JY (2003) Development of a machining simulator considering machine behaviour. Proc Inst Mech Eng B J Eng Manuf 217(9):1333–1339

20. Seo TI, Dépincé P, Hascoet JY (1997) Paths compensation for tool deflection in end milling. Ifac-Ims Intelligent Manufacturing Systems. Seoul (Korea), July 21–23
21. Sokolov A, Richard J, Nguyen VK, Stroud I, Maeder W, Xirouchakis P (2006) Algorithms and an extended STEP-NC-compliant data model for wire electro discharge machining based on 3D representations. Int J Comput Integr Manuf 19(6):603–613
22. Laguionie R, Rauch M, Hascoet J-Y (2009) Simulation and optimization in a multi-process environment using STEP-NC. IEEE ICCA 2009:2384–2391
23. Newman ST, Nassehi A (2007) Universal manufacturing platform for CNC machining. CIRP Ann Manuf Technol 56(1):459–462
24. Suh SH, Shin SJ, Yoon JS, Um JM (2008) UbiDM: a new paradigm for product design and manufacturing via ubiquitous computing technology. Int J Comput Integr Manuf 21(5):540–549
25. Laguionie R, Rauch M, Hascoët JY, Suh SH (2011) An eXtended manufacturing integrated system for feature-based manufacturing with STEP-NC. Int J Comput Integr Manuf 24(9):785–799
26. Rauch M, Laguionie R, Hascoët JY, Xu X (2009) Enhancing CNC manufacturing interoperability with STEP-NC. J Mach Eng 9(4):26–37
27. IEC 61499 (2005) Function blocks for industrial-process measurement and control systems-part 1: architecture
28. Hentz JB, Nguyen VK, Mader W, Panarese D, Gunnink JW, Gontarz A, Stavropoulos P, Hamilton K, Hascoet JY (2012) An enabling digital foundation towards smart machining. CIRP ICME 2012
29. ISO14649-13 (2003) ISO14649 part13—industrial automation systems and integration—physical device control-data model for computerized numerical controllers—part 13, process data for wire-EDM. TC 184/SC 1
30. Sokolov A, Richard J, Nguyen VK, Stroud I, Maeder W, Xirouchakis P (2006) Algorithms and an extended STEP-NC-compliant data model for wire electro discharge machining based on 3D representations. Int J Comput Integr Manuf 19:603–613
31. Bonnard R, Mognol P, Hascoet JY (2008) Rapid prototyping project description in STEP-NC model. In: Proceedings of the sixth CIRP international seminar on intelligent computation in manufacturing engineering, Naples, Italy
32. Babic B, Nesic N, Miljkovic Z (2008) A review of automated feature recognition with rule-based pattern recognition. Comput Ind 59:321–337
33. Barnes S, Timms N, Bryden B, Pashby I (2003) High power diode laser cladding. J Mater process Technol 138:411–416
34. Xu X et al (2006) STEP-compliant process planning and manufacturing. Int J Comput Integr Manuf 19:491–494