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Interoperable CNC System for Turning Operations

Yusri Yusof, Stephen Newman, Aydin Nassehi and Keith Case

Abstract— **The changing economic climate has made global manufacturing a growing reality over the last decade, forcing companies from east and west and all over the world to collaborate beyond geographic boundaries in the design, manufacture and assemble of products. The ISO10303 and ISO14649 Standards (STEP and STEP-NC) have been developed to introduce interoperability into manufacturing enterprises so as to meet the challenge of responding to production on demand. This paper describes and illustrates a STEP compliant CAD/CAPP/CAM System for the manufacture of rotational parts on CNC turning centers. The information models to support the proposed system together with the data models defined in the ISO14649 standard used to create the NC programs are also described. A structured view of a STEP compliant CAD/CAPP/CAM system framework supporting the next generation of intelligent CNC controllers for turn/mill component manufacture is provided. Finally a proposed computational environment for a STEP-NC compliant system for turning operations (SCSTO) is described. SCSTO is the experimental part of the research supported by the specification of information models and constructed using a structured methodology and object-oriented methods. SCSTO was developed to generate a Part 21 file based on machining features to support the interactive generation of process plans utilizing feature extraction. A case study component has been developed to prove the concept for using the milling and turning parts of ISO14649 to provide a turn-mill CAD/CAPP/CAM environment.**

I. Introduction

Today, with the use of computer technologies and communication technologies in the manufacturing industries, manual and semi-automatic methods are largely being replaced by Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) to implement concurrent engineering [1]. Widespread CADCAM systems will reduce human interaction and the result, should be increased production, reduced costs and better quality of product. CNC machines now, utilize a variety of cutting technologies such as multi turrets and multi spindles in various axial configurations increasing the level of complexity compared to the machines of the previous decade [2]. A large number of CAx systems have been developed and implemented in recent years to support all stages of product life by computer systems and many can simulate virtual CNC machining with the complete machine toolpath [3]. Most of these systems are specialized to support certain applications, and are based on an information model that handles the application specific view of the product. These CAx systems do not share common databases for the product information. Since the first NC machine was introduced in 1947, various process planning packages have been developed and each system tried to interpret the part data format more reliably. To date there are more than 2000 CNC models around the globe, and turning centers need a single standard particularly in the area of machining to improve productivity by increasing the richness of interactions and transactions. An initial standard is ISO 10303, informally known as the STandard for the Exchange of Product (STEP) Data which aims to provide a single International Standard for all aspects of technical product [4]. This paper presents an overall review of the various research projects carried out by the major research groups. The relevant research issues for the development and introduction of reconfigurable machines tools are presented focused on turning operations. Finally, the authors propose a STEP-NC compliant CAD/CAPP/CAM system that is currently being implemented at Bath University, UK and UTHM, Malaysia. A case study based on a component from industry has been carried out to demonstrate the capability of the system.

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Yusri Yusof is with the Faculty of Mechanical and Manufacturing Engineering, University of Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Johor, Malaysia. Phone: +607-4537982; fax: 607-453 6353; E-mail address: yusri@uthm.edu.my.

Stephen Newman is with the Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, United Kingdom. Tel.: +441225 386934; fax: +441225 386928. E-mail address: S.T.Newman@bath.ac.uk

Aydin Nassihe is with the Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, United Kingdom. Tel.: +441225 384801; fax: +441225 386928. E-mail address: A. Nassehi@bath.ac.uk

Keith Case is with Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom. Tel.: +44(0)1509 227654; fax: 44 (0) 1509 227 648. E-mail address: k.case@lboro.ac.uk

II. Review of STEP-Compliant Manufacturing for Turning Operations

A. STEP-NC Environment for Manufacturing

ISO 14649 is referred to as STEP-NC due to its interaction with ISO 10303 (STEP) and was initiated to provide a data model for a new breed of intelligent CNC controller that is well-structured with workplans and workingsteps. ISO 14649 aims to model the complete information requirement that must exist in a controller to control a machine tool by defining "what-to-make" and plans "how-to-make". STEP-NC has been developed as a result of several research projects carried out by companies and academic institutions. In terms of international research and development into these standards, projects such as OPTIMAL [5] largely overcame the legacy standards of ISO 6983. OPTIMAL is one of the earliest STEP-compliant systems and is based on feature information and machining strategies. The research does not stop there, because the researchers now focus on identifying and defining interoperable manufacturing and STEP-NC compliance in the context of concurrent engineering. In particular, information reviews of STEP-NC, manufacturing processes and manufacturing resources are also major foci in this research area. STEP-NC is aimed at overcoming the problems left from ISO 6983 which focuses on programming the path of the cutter centre location (CL) referred to the machine axes rather then machining tasks. One approach to the problem is to exchange a high level of information between CADCAM systems and NC controllers. STEP-NC works by manufacturing features, operations and the workingsteps. The STEP-Compliant Data programming interface for numerical controls has been introduced and proposed for standardization by the International community, where its higher level of information aims to overcome the shortcomings of contemporary NC programming. The new NC programming data model purports to support a well structured hierarchical interface, and object-oriented and two way communication from the CAD environment down to the shop floor [6]. STEP-NC is an improved interface between the CAD world and the manufacturing arena. It is recognized as such since it provides process information at the time and place of the manufacturing activity. The proposed STEP-NC data format supports accurate and timely adaptive control of the production equipment and provides feedback for information back to the planning activity.

The current standard of programming NC namely G & M codes or ISO 6983 has had no significant change since the format of NC machines was developed at MIT in 1952 [7-10] and the evolution of NC machines since using hardwired configurations to the current fully-integrated systems that can be found almost everywhere, from small job shops in rural communities to multi-national companies in large urban areas. During the pre-Computer-Numerical Control (CNC) epoch the program language had been modified by vendors and controller developers who added their own commands. Since the 1970's significant developments have been made towards more automatic and reliable computer numerically controlled machines with new machining processes. Today's highly sophisticated Computer Numerically Controlled (CNC) machines utilize a variety of cutting technologies such as multi-turret and multi-spindle in complex axial configurations and this machine capability increases the level of flexibility and capability compared to the previous decade [11]. A large number of Computer Aided Systems (CAx) have been developed and implemented in recent years to support all stages of product life by computer systems and many can simulate virtual CNC machining with the complete machine toolpath [3]. Since the first NC machine was introduced in 1952, various process plan packages have been developed and each system tried to interpret the part data format more reliably. Most of these systems are specialized to support certain applications, and are based on an information model that handles the application specific view of the product. These current trends are aimed at open systems but they are predominantly used in retrofitting applications for conventional NC machines. Some of the CAx systems do not share common databases for the product information due to the resistance from software and hardware vendors in terms of business strategy.

B. *Review of STEP-Compliant Manufacturing for Turning*

One of the aims for the next generation of CNC machines is to be interoperable and adaptable so that they can respond quickly to changes in market demand and the manufacturing needs of customized products [12]. As part of this, 2006 was a time when researchers were particularly focused on proposing a framework for turning. Most of the researchers proposed prototype systems to support data interoperability between the various CAx systems based on ISO standard 14649 that provided the first data exchange format used in the operation of NC machines as shown in Table 1. Among these systems, G2STEP is the latest system to cover the machine functioning from pre-processor to STEP-NC part program generation including part program verification [13].

TABLE 1
REVIEW OF STEP-COMPLIANT SYSTEMS

No	Systems	Input	Output	Domain
1	***SFPS*** *(Milling) [14]*	*STEP AP203 & AP214*	*Part program physical file (text)*	*Prismatic*
2	***STEPTurn*** *[15, 16]*	*STEP AP203*	*Part program physical file (text)*	*Rotational*
3	***TurnSTEP*** *[17, 18]*	*STEP AP*	*ISO 14649 physical file and extensible mark-up language (XML)*	*Rotational*
4	***G-Code Free for lathe*** *[19, 20]*	*STEP AP 203*	*Native CNC language program*	*Rotational*
5	***G2STEP*** *(2-axis turning machining) [13]*	*G-codes*	*STEP-NC part program*	*Rotational*

This development of a future manufacturing platform to enable different processes and capability such as milling applications, multi-axis and complex components as the basis of the integration of CAD/CAPP/CAM and CNC will be a major research task for years to come. For the time being many obstacles come from software/hardware vendors as the current approaches give them many opportunities to maintain their market, but the new standards can provide the platform for the future of global interoperable manufacturing [21]. The Shop-floor Programming System (SFPS) introduced by Suh is the first system fully compliant with ISO 14649 [14] and to date, only this system has been patented (US patent references; 6400998, 6511961, 6556879, 6650960 and 6671571). There is no doubt, that so far none of the proposed systems are fully capable of machining turn/mill components. Work to date has focused on the separate parts of ISO 14649 using Part 11 for milling operations including drilling and Part 12 for turning. No significant work has been done on combining the two parts for turn/mill components. However, the authors and some researchers [15] believe that this industrial requirement could be achieved through research and development involving collaboration by researchers, users, manufacturers, academia and the ISO committee. If developers look from the business perspective, and academia focuses on theoretical aspects the objective of combination turning and milling machining compliance with the new standard (STEP-NC) can be realized. If we focus on turning operations, only three proposed systems are available, STEPTurn, TurnSTEP and G2STEP. But, if we scope for e-manufacturing, STEPTurn leads in this aspect due to the capability of internet file transfer. TurnSTEP clearly defines the number of set-ups as either one set-up or two set-ups dependent on the independent machine format [18].

TurnSTEP has some weaknesses such as threads cannot be automatically generated but need to be defined and the process plan graph edited by the user manually. The output of this system can be in text and XML file formats [18]. As reported TurnSTEP is at a prototype stage and the implementation of another part, which is intelligent and autonomous is still under development. In terms of implementation of bi-directional information flow, none of the systems show how it would work and do not make it clear how the functionality is supported in prototype systems. So far the test components used contain only simple turning operations with z and x axes and do not cover multi-axis machining. The authors strongly agrees with the suggestion by Heusinger and Rosso-Jr, for the STEP-NC compliant information structure to support the milling capability of the NC turning centre to meet industrial needs mapped by ISO 14649 Part 11 and 12 (milling and turning) [15, 22]. The authors have noticed that all the proposed systems use a feature recognition approach and feature based techniques to allow the user to edit the part program. Xu has stressed that the commercial software, namely ST-Plan, can create STEP AP 224 machining features from CAD files (AP 203 or AP 214) [10]. All the proposed systems comply with ISO 14649 and this is the first stage to develop the universal manufacturing platform for CNC machining as proposed by [17, 21].

III. Design of a STEP Compliant System for Turning Operations (SCSTO)

The fundamentals of planning a machining process in a numerically controlled environment lie with the control and quality of operation planning and that planning time represents 50 to 80 percent of the actual machining time for single parts or small batches [8]. It becomes more critical for complex situations and new manufacturing technologies tend to extend the time further. Process planning has been defined by [23] as a function within the manufacturing environment which deals with the selection of manufacturing processes and parameters to be used to create the final product [23]. Investigations by Younis showed that an efficient CAPP system could result in reduction of the manufacturing costs by up to 30% and would also reduce the manufacturing cycle and the total engineering time by up to 50% [24]. Hence, the focus has been on process planning as the task of the determination of manufacturing processes, which for instance can determine whether or not a product should be manufactured through turning operations. This section proposes a system framework for a STEP Compliant System for Turning Operations (SCSTO) which considers both informational and functional perspectives of the system. From a functional perspective the proposed system has been designed to be a semi-automatic process planning system, meaning that it does not automatically generate manufacturing information directly from the CAD model. It is aimed at the creation of feature-based process plans for manufacturing processes such as turning operations.

The proposed system is for turning operations and is based on a STEP compliant environment. It consists of several elements that define turning features and generate STEP code compliant with ISO 10303 Part 21 [25]. The system is based on feature-based design and begins with the selection of the workpiece followed by the choice of turning manufacturing features and finally the choice of the tools. The output of the system is a physical file complying with Part 21 [25]. The aim of this work is to address the process planning and machining of rotational components and to propose a STEP Compliant NC structure for generation of ISO 14649 code which can be used for turning component manufacture. Interoperability within this context is a significant objective. Interoperability is defined as the ability to integrate STEP-NC compliant information in the product life cycle including CAD, CAPP, CAM and CNC, combined with feasible information structures to represent various configurations of turning machining centers. The overall framework is based on the Java programming language. The prototype has been developed using JBuilder 2005 [26] to provide a suite of integrated development tools related to STEP standards. This concept has been used to generate java classes from the EXPRESS schema and to handle the STEP Part 21 physical file format. The data model for manufacturing of turned components was based on the ISO 14649 standard. Part 10 is the backbone of the standard covering the common data structure. In the standard, the part is defined as a *workpiece* while the task is defined as a *workplan* consisting of a series of *machining_workingsteps* to carry out the *machining_operation* on a *manufacturing_feature*. In turning operations it becomes a workplan with a series of *turning_workingsteps* to carry out the *turning_operation* on a *turning_feature*. The *turning_operation* itself is supported by *turning_technology, turning_machine_function* and *turning_strategy*.

The UML was developed representing the representation and model diagrams, the constraints and the extension mechanisms. UML is the most widely known and used standardized notation for object-oriented analysis and design. The most useful standard UML diagrams are; use case diagram, class diagram, sequence diagram, state chart diagram, activity diagram, component diagram and deployment diagram. For the purposes of this paper, only class diagrams and their notation have been used. In order to develop the system, a set of computing tools will be used. The Java programming language is used for the actual development of software components based on the object oriented methodology and UML is utilized as the modeling language. The manufacturing models refer to the process that deals with production such as operation and strategies. The UML represents the various objects for the SCSTO manufacturing environment and the relationships between these objects as shown in Figure 1 [27, 28]. Each data type in these models is based on ISO 14649 part 10 [29] and part 12 [30] and UML

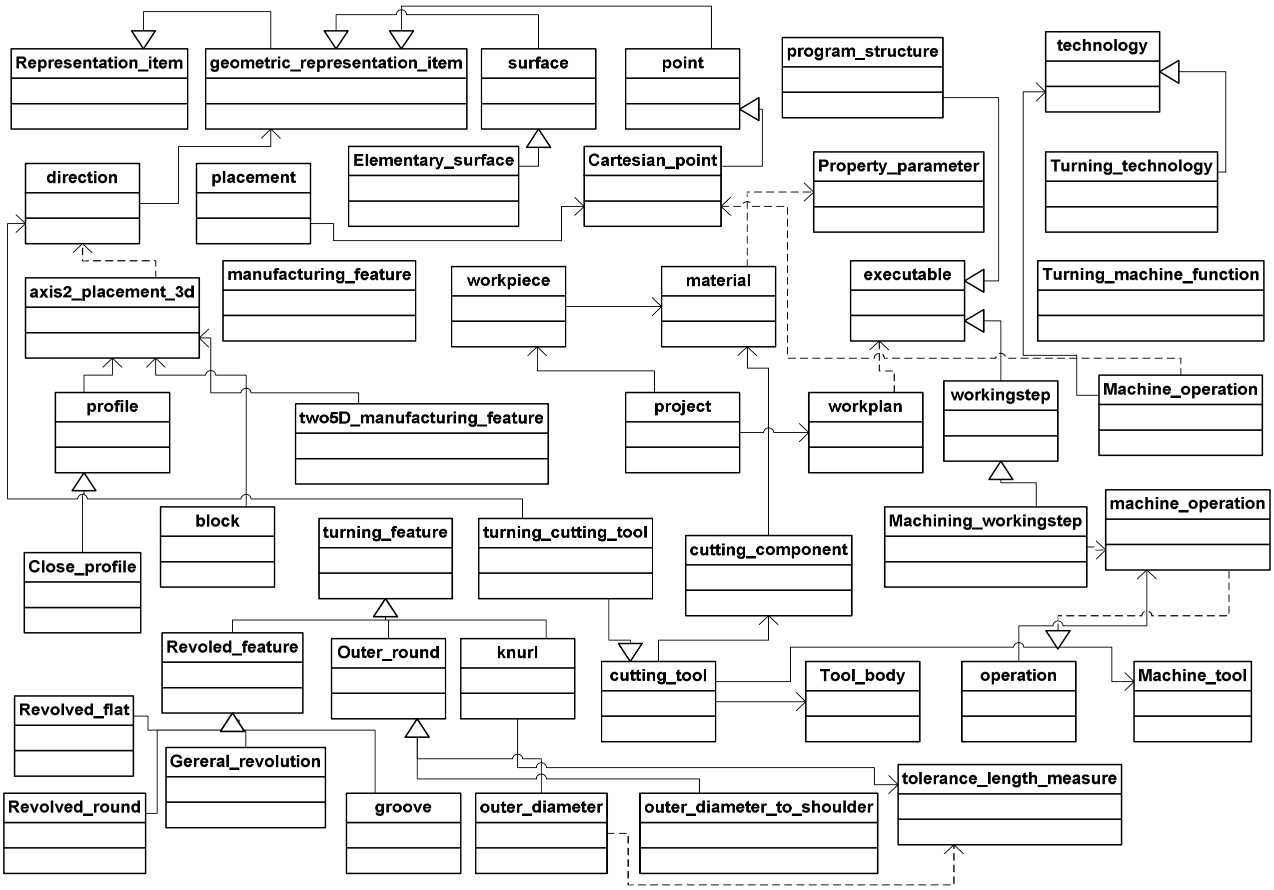

Figure 1 UML Diagram for SCSTO [27, 28]

It starts with gathering the information related to SCSTO, focuses on the product and manufacturing models to provide additional input into the construction of the model and forms the basis of the conceptual information. A sample of code containing the implementation and structure of one the most general class turning feature library and the code consists of public class, constructors and methods. Finally after considering the product data model and the manufacturing data model referring to manufacturing resources, processes and strategies the authors has developed a model for SCSTO using STEP-NC schemas. This model becomes a platform for developing the SCSTO prototype based on functional and information referring to resources, processes and strategies. The overall system consists of three main subsystems; manufacturing features creator, manufacturing operations and program generator. In SCSTO, the user has a choice to either create a new project with new features or open a project from a CAD file in STEP AP 203 format. Geometry described in the AP 203 format defines the features but not their location and orientation. Feature geometry is defined in ISO 14649 Part 12 [30] and more formally described in terms of UML diagrams. The placement and location of the feature needs to be provided by the user once the feature has been extracted from the AP

203 file. The alternative is to create the feature by user definition which is limited to features within the feature library. If the user needs to define a new feature, the first step in designing a part is to specify the base part shape and the dimensions associated with the shape to define its size. In this thesis the base part shape is limited to cylindrical, so only this shape can recognized for further processing. The base part shape is considered as the initial shape of the material before machining the features. Cylinder length and diameter are the only parameters needed to define the base part that is positioned with the z-axis parallel to the longitudinal axis of the shape. The x and y-axes are orthogonal to the z-axis. The axis origin is positioned at the centre of the circular profile forming the bottom of the cylindrical base part. The second subsystem consists of five major components:

i. Integration and preparation of part design data.
ii. Selection of machining strategy
iii. Selection of machining technology.
iv. Selection of machine functions.
v. Selection of cutting tools

The third subsystem is the Generation of Process Plans to generate a physical STEP-NC process plan file. This file consists of information such as machining operations, cutting tools, machining parameters, etc. If the user is not satisfied with this part program, it can be edited to modify either turning features or turning operations. The turning machining concept is based on 2D profiling except for drilling perpendicular to the z axis. The product model is contained within a set of interconnected objects. The class definition of these objects is based on the entity definitions that exist within the ISO 14649 standard. From the standard, classes are written in the java language and an example of the structure of these classes.

The SCSTO system adheres to the Windows standard for user interface design. All functions can be accessed from the pull-down menus, and common functions are accessible via toolbar icons. Figure 2 shows the SCSTO user interface window. It consists of several pull-down menus and toolbars. One of the major functions of the proposed system is machining operations, to manufacture the part. Generally, there are two types of machining operations: roughing and finishing. Roughing is used to remove material from the original raw material by multiple surface passes down to the finishing allowance. Finishing then removes the finishing allowance to yield the final form of the feature. The operation is one of the following: facing, grooving, contouring, threading, or knurling and for milling, drilling, boring, centre drilling and reaming. Due to special machining the proposed system covers all types of turning machining and only drilling under milling operations as defined in ISO 14649 Part 11 [31]. The drilling operations have been combined together with turning operations.

IV CASE STUDY COMPONENT

Machining operations for case study component are turning, grooving, threading, off centre drilling and milling on the side face. Its general attributes are double-sided and asymmetrical. The main contribution of this case study is to show the ability of SCSTO to read from a CAD file and recognize all the features with definition of turning technology, turning strategies, defining tools, workplan and workinsteps. This description focuses on the imported file and the recognition of the features.

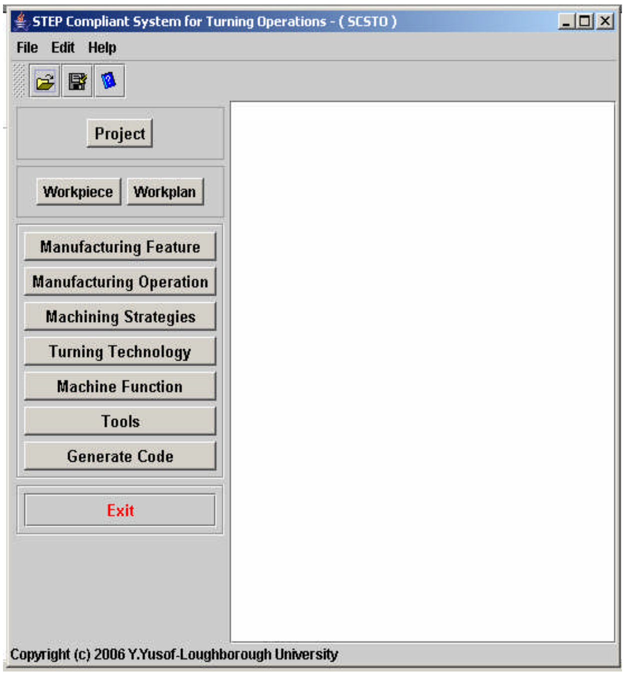

Figure 2 The SCSTO user interface window

The main purpose of this case study is to investigate the prototype system's capability of creating features directly from a CAD file. The case study component has been designed in Unigraphics software, exported as a STEP AP 203 file and then imported into SCSTO. Case study component has a minimum of one set-up if the machine has a counter spindle and two-sided machining. The complete machining process involves twenty three processes and also depends on the machine configuration. This demonstration for case study component starts with the user beginning the modeling process by selecting the base part as the cylinder type. This shape is considered as the starting raw material for modeling the component. Then the user creates a step feature and attaches it to the base part. The remaining features are created and attached to the base part. The component was created in Unigraphics (UG) version NX3 to export file based on UG environment. Finally, an ISO 14649 part program is generated by clicking the Generate Code button. The program is based on workpiece and *machining_workingsteps* in a physical file text format. This text file can be saved to a selected directory folder. As mentioned the part program can be edited by the user based on manufacturing features, strategies, tools, etc. When the user has finalized the part program, it can be sent to the machine controller. The manufactured product after the finishing process is shown in Figure 3.

Figure 3 Final product (top-view) for component

I. V Conclusions

This research work was motivated by industrial requirements of concurrent engineering, standard product data models and an integrated manufacturing environment, which are further reflected in process planning. The conclusions of the work can be elaborated as:

i. The information modeling in this area addresses the problem of capturing and representing manufacturing information related to resources and processes. The interaction between the different types of models could provide a description of the products, how they should be manufactured, and what manufacturing resources should be used. This would provide an information platform upon which several different computer-based tools to support the innovation process can be built. This will allow the provision of reliable manufacturing information to assist in the performance of product development life cycle activities and related decisions.
ii. SCSTO was developed to generate a Part 21 file based on machining features to support the interactive generation of process plans utilizing feature extraction. The system was constructed using a structured methodology for its planning and object-oriented methods for its implementation.
iii. A case study component was tested to show that the new approach (STEP-NC) can generate code which is comparable to the currently used G-code with some benefits such as the elimination of the post-processor.
iv. Efforts are under way to fulfill the STEP-NC challenge by combining Parts 11 and 12, for turn/mill operations. STEP-NC forms a possible basis to satisfy the latest requirements and demands with respect to a bi-directional CAx process chain for machining.
v. STEP-NC forms a possible basis to satisfy the latest requirements and demands with respect to a bi-directional CAx process chain for machining. In addition its development as a future manufacturing platform to enable different process models to be integrated for the adaptable integration of CAD/CAPP/CAM and CNC will be a major avenue of research for years to come.

It is expected that the recommended future extensions will enhance the usefulness of this paper, and will meet the requirements for global interoperable manufacturing for real-life parts.

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