Loughborough University

STEP Compliant CAD/CAPP/CAM System For Rotational Asymmetric Parts

By

Roberto Silvio Ubertino Rosso Junior

A Doctoral Thesis

Submitted in Partial Fulfilment of the Requirements

for the Award of Doctor of Philosophy of

Loughborough University

Wolfson School of Mechanical and Manufacturing Engineering

August 2005

Loughborough University

To my wife Márcia

and to my son Enrico

Acknowledgements

I wish to express my sincere gratitude to my supervisors, Dr. Stephen T. Newman and Dr. Shahin Rahimifard, for their direction, support, patience and friendship. I am sure that would be harder to finish this work without your support.

I wish also to say thanks to Dr. Robert I. M. Young who invited me to come to Loughborough University and shared part of his knowledge about standards. Thanks for the nice chats.

I would like to thank the technical support and administration staff of Wolfson School, especially to Robb Doyle, David Walters, John Jones, Richard Price, Derrick Hurrell, Jagpal Singh, Clive Turner, Jo Mason, Cathy Turner, Sheralyn Thorne and Sue Cramp.

This was a long journey where I met many friends. I wish to thank Dr. Dean England, Dr. Adrian Espinosa, Dr. Aysin Rahimifard, Dr. Shaofeng Liu, Dr. David Guerra Zubiaga and Mr. J. Francisco Moreira for their friendship throughout the research.

I would also like to thank the people that participated in the discussions of the workgroup ISO TC184/SC1/WG7 especially to Mr. Stefan Heusinger(University of Stuttgart) and Mr. Jochen Wolf(WZL-Aachen) which with I spent many hours in real and "virtual" chats throughout these years.

Acknowledgements are due to Loughborough University and the to CNPq (National Council of Research – Brazil) for the financial support for this research. Also, the State University of Santa Catarina (Brazil), UDESC, for granting me study leave.

I am very lucky and got a 'new family' here in Loughborough. Thanks to Matthew, Elaine and Ryan Beaken for your friendship to my family.

Special thanks must go to my parents Roberto and Sandra and to my sisters Helena and Isabelle. I would never become who I am without their love.

Abstract

Manufacturing integration has been sought out for a number of years. Standardised information sharing has been an issue to guarantee computational systems interoperability across the product life cycle, but particularly in the manufacturing phase. The International Standard that supports product information namely ISO 10303 has supported computer aided systems in the product information exchange and sharing. However, standards for manufacturing information have been a problem waiting for solutions. In recent years product and manufacturing models have been used to support computational systems. However, the lack of an International Standard to represent the manufacturing information was an obstacle to have interoperable systems in the so-called CAx process chain.

This thesis reports research on information support for computer aided process planning and manufacture with the basis on the new NC standards that support information exchange between CAD and CNC. A novel brand of product and manufacturing model has been explored to represent information necessary to support the process planning activity that uses new parts of ISO 10303 standard and the evolving ISO 14649 standard. The work also focuses on the understanding and development of the aforementioned standards with the aim to support and to integrate computer aided design, process planning and manufacture. The structure of the manufacturing model is based on three classes namely workingstation capability, process capability and resources capability. These provide the necessary infrastructure for interoperable computational systems that support the CAx process chain.

The models have been tested through a case study using a proposed computational prototype entitled the STEP-TM CAPP system. This prototype shows this research approach provides significant potential for the future interoperable process planning of parts for the next generation of CAPP/CAM systems to make effective use of the future ISO14649 intelligent CNC controllers.

Abbreviations

AECMA	The European Association of Aerospace Industries
APT	Automatically Programmed Tool
B-Rep	Boundary Representation
CAD	Computer-Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacture
CAM-I	Computer-Aided Manufacturing – International
CAPP	Computer-Aided Process Planning
CIM	Computer Integrated Manufacturing
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
ESPRIT	European Strategic Program for Research in Information Technology
ICOM	Input, control, output, mechanism.
IDEF0	ICAM Definition Level 0
IDEF1x	ICAM Definition Level 1x
IGES	Initial Graphics Exchange Specification
ISO/TC184	Technical Committee 184, Industrial automation systems and integration.
NC	Numerical Control
PDDI	Product Definition Data Interface. A USAF Project
PDES	Product Data Exchange Standard
ProSTEP	Association for the Advancement and Support of International Product Data Standardization
RAMP	Rapid Acquisition of Manufactured Parts
SC4	Subcommittee 4, Industrial data
SC1	Subcommittee 1, Physical device control
SCRA	South Carolina Research Authority
SET	Standard d'Exchange et Transfer. French Data exchange standard
STEP	Standard for the Transfer and Exchange of Product Model Data
VDA/FS	Verdand des Automobilindustrie Flachen Schnittstelle. A German extension of IGES for the transfer of surface data
WG7	Work Group 7 of Subcommittee 1, ISO/TC184
XML	Extensible Markup Language

Table of Contents

Acknowledgements II

Abstract IV

Abbreviations V

Table of Contents VI

Chapter 1 : Introduction 1

Chapter 2 : Research Scope 5

2.1 Introduction 5

2.2 Research Aims and Objectives 5

2.3 Research Scope 7

2.3.1 Review the literature relating to STEP standards, CAD/CAPP/CAM/CNC and features based research 7

2.3.2 Specification of a framework to support STEP compliant NC manufacture 7

2.3.3 To investigate and realise a STEP compliant information model for asymmetric rotational parts 7

2.3.4 Explore the use of feature technology with a STEP compliant approach 8

2.3.5 Realisation of a STEP compliant CAPP/CAM computational prototype 8

2.3.6 Demonstration (Component) verification 8

Chapter 3 : Review of Computer Aided Process Planning and Manufacturing Using Features and Information Models

3.1 Introduction 9

3.2 An Overview of Computer Aided Design 9

3.2.1 Wireframe Models 9

3.2.2 Surface Models 10

3.2.3 Solid Models 10

3.3 An Overview of Process Planning 11

3.3.1 Manual Process Planning 12

3.3.2 Computer Aided Process Planning 12

3.3.2.1 Variant Approach 12

3.3.2.2 Generative Approach 14

3.3.2.3 Hybrid and/or Semi-Generative Approach 14

3.4 Computer Aided Manufacturing and CNC 15

3.4.1 The foundations of manufacturing support systems 15

3.4.2 Current trends in Commercial CAM systems 16

3.5 Overview of Feature Technology 16

3.5.1 Features Concept 17

3.5.2 Features Classification 19

3.5.3 Features Benefits 20

3.5.4 Feature Based Approaches 20

3.5.5 Human feature Recognition 20

3.5.6 Design by Features (DBF) 20

3.5.7 Automatic Feature Recognition (FRec) 22

3.5.8 The Hybrid Approach: Design-by and Features Recognition (HDR) 22

3.6 Application of Features in Modelling and Manufacturing of Parts 23

3.6.1 Features Related to Prismatic Parts 23

3.6.2 Features Research Related to Rotational Parts 24

3.6.3 Use of Features for Asymmetric Rotational Parts 25

3.7 Concepts of Information Models 26

3.8 Summary on CAD/CAPP/CAM Systems and information models 28

Chapter 4 : Review of Standards for Information Exchange

4.1 Introduction 29

4.2 The Methods for Data Exchange 29

4.3. Early Standards for Design and Manufacture 31

4.4. The STEP Standard Concepts and Structure 33

4.4.1 Structure of the Standard 33

4.4.2 Description Methods 34

4.4.3 Integrated Resources 35

4.4.4 Application Protocols 35

4.4.5 Implementation Methods 35

4.4.6 Conformance Tools 36
4.4.7 AAM - Application Activity Model 36
4.4.8 ARM - Application Reference Model 37
4.4.9 AIM - Application Interpreted Model 37
4.4.10 AIC – Application Integrated Constructs 38
4.5 The EXPRESS Language 38
4.6 The standards related to ISO 14649 39
4.6.1 AP 203 - Application Protocol: Configuration Controlled 3D Designs of Mechanical Piece Parts and Assemblies 39
4.6.2 Part 224 - Application Protocol: Mechanical Product Definition for Process Planning Using Machining Features 41
4.6.3 Part 240 - Application Protocol: Process Plans for machined Products 43
4.6.4 AP 219 – Dimensional Inspection Planning 45
4.6.5 AP 238 - Application Interpreted Model for Computerized Numerical Controllers 46
4.7 Review Summary 47

Chapter 5 : Review on STEP Compliant Manufacturing

5.1 Introduction 49
5.2 Background 49
5.3 The Standard ISO 6983 51
5.4 The ISO 14649 Standard 54
5.5 The Structure of the ISO 14649 Standard. 57
5.5.1 ISO 14649 Part 1 – An Overview and Fundamental Principles 58
5.6 ISO 14649 Part 10 - General Data Process 60
5.7 ISO 14649 Part 11 - Process Data for Milling 68
5.8 ISO 14649 Part 111 - Tools for Milling 75
5.9 ISO 14649 Part 12 - Process Data for Turning 78
5.10 The ISO 14649 Part 121 - Tools for Turning 83

Chapter 6 : Frameworks for a STEP Compliant Turn/Mill CAD/CAPP/CAM System

6.1 Introduction 88

6.2 A Vision Towards a Higher Level of NC Programming 88

6.3 Implementation Frameworks Towards a STEP Compliant CAD/CAPP/CAM Environment 89

6.3.1 A CAD/CAM System which Imports/Generates STEP-NC Information 90

6.3.2 A CAD/CAM System with STEP-NC Data Support Structures 91

6.3.2.1 A CAD/CAM system integrated with an external STEP-NC data support system 91

6.3.2.2 A CAD/CAM environment with both native and STEP-NC internal data structures 92

6.3.3 A CAD/CAM Environment with Kernel STEP-NC Data Structure 93

Chapter 7 : Design and Specification of a STEP Compliant CAPP/CAM System

7.1 Introduction 94

7.2 Design of STEP Compliant CAPP/CAM 94

7.3 Information Models to Support the STEP Compliant CAPP/CAM 96

7.4 STEP Compliant Product Model 97

7.5 STEP Compliant Manufacturing Model 98

7.6 Modelling the Resource Capabilities 101

7.6.1 The Raw Material Class 102

7.6.2 Manufacturing Machine Tool Resources Class 103

7.7 Modelling the Process Capabilities 109

7.7.1 Turning Machining Operation Class 111

7.7.2 Milling Machining Operation Class 111

7.7.3 Turn Mill Machining Operation Class 112

7.8 Requirements of the STEP Compliant CAPP/CAM Model 113

7.8.1 STEP Compliant Turn-Mill CAPP/CAM 114

7.8.2 The Feature Identification 115

7.8.3 Generate STEP Compliant Process Plan Activity 116

7.8.4 Code Generation 118

Chapter 8 : Realisation of a STEP Compliant Turn/Mill CAD/CAPP/CAM Environment

8.1 Introduction 120

8.2 Operational Structure of the CAx System 120

8.3 Case Study 121

8.4 System Control Interface 122

8.5 Data Base Maintenance Module 123

8.6 Product Information Retrieval Module 129

8.7 Process Plan Module 129

8.7.1 Fixtures and Set-ups Selection 130

8.7.2 Operations and Strategies Definitions 132

8.7.3 Machine Tool Selection 132

8.7.4 Tools and Cutting Parameters Selection 134

8.7.5 Machine Functions Definition 136

8.7.6 WorkingSteps and WorkPlans Generation 137

8.7.7 WorkingSteps Sequencing and Optimisation 138

8.8 Program Generation 140

8.9 Non STEP-NC Machine Specific Program 140

Chapter 9 : Concluding Discussion

9.1 Introduction 141

9.2 Review the literature relating to STEP standards, CAD/CAPP/CAM/CNC and features based research 141

9.2.1 STEP-NC standards development 142

9.2.2 Comparison of STEP-NC and programming methods 143

9.3 Specification of a framework to support a STEP compliant NC manufacture 144

9.4 Explore the use of feature technology with a STEP compliant approach 145

9.5 To investigate and realise a STEP compliant information model for asymmetric rotational parts 146

9.6 Realisation of a STEP compliant CAPP/CAM computational prototype 147

9.7 Case study component system demonstration 148

Chapter 10 : Conclusions

10.1 Introduction 149

10.2 Conclusions 149

10.3 Further work 151

10.3.1 Integration of AP 238 within the Manufacturing Model 151

10.3.2 Extend the Manufacturing Model to other technology 152

10.3.3 Programme implementation 153

10.3.4 Implementation on a neutral persistent data/information base. 153

10.3.5 Future Vision for STEP-Compliant CAx Systems 153

References 154

Appendix - Author's Research Papers 176

Chapter 1

Introduction

Global competition has driven companies worldwide to improve their production methods. The changes in market demands requires that companies be more flexible and agile in order to meet customer expectations and overcome the challenge of the competitors. The need to build quality assured products at a lower cost, tailored to customer's needs has pushed the boundaries of the industrial environment in the second half of the 20th century. In the metal-mechanical industries, the use of computers has improved productivity and significantly shortened the cycle of design, planning and manufacturing.

In this scenario, data, information and knowledge are key assets to success. Currently the need to have well integrated manufacturing systems is more and more urgent as the product lead time from design to market has been shortened by market demands and competition. This implies that the manufacturing process chain needs better integration from the design to the actual manufacturing phase.

At the heart of the manufacturing phase is Numerical Control(NC) technology which is now over fifty years old. Over this period there have been remarkable developments in NC machine designs and in processing capabilities, together with controllers which have changed dramatically from the early generation of hardwired conventional numerical control to today's high powered PC-CNC controls. Even today the standard language used in manufacturing is still based on the movement and status of the machine through G/M codes (ISO 6983). From the integration view point, this is a major drawback as the NC part programmes created in this traditional manner lose much of the information such as geometry and tools' description. Apart from this, the standard for the NC programming language, ISO 6983, is open to interpretation allowing each vendor to create its own dialect. The result is a loss of interoperability and inability to have bi-directional integration between Computer Numerical Controlled(CNC) machines and the off line systems.

A significant body of research has identified that the use of integrated information models is a way to achieve data sharing and interoperability among the many parts of the product development and life cycle. It is the author's belief that these information models should comply with standards in an era when enterprises are exchanging and sharing information either internally or globally. Thus, standardised information should be able to be accessed by different systems though it is vendor independent.

The central core of this research relates to the development of both theoretical and functional requirements to design and evaluate a CAPP/CAM system based on the new NC program structure assigned in the ISO 14649 standard. The research described in this thesis uses the ISO 10303 standard (STEP) and the emerging ISO 14649 standard (STEP-NC) which represents data models for numerical control interfacing to achieve integration across the design, planning and machining chain through the use of an overall information model infrastructure. The research reported in this thesis is focused on the specification and definition of a set of STEP compliant information models to support the planning and manufacturing activities for a new generation of CAPP/CAM systems, their challenges and possible solutions. The information model requirements and the implementation issues are explored for asymmetric rotational parts.

The increasing use of combined milling and turning operations using turning centres or machining centres with turning capabilities open a new avenue to investigate a special case of implementation of the combined milling and turning operations as these provide the way to define design and manufacturing information for asymmetric rotational parts. As the ISO 14649 (STEP-NC) standard is still in its infancy and beginning to develop a data model for combined mill/turn operations, the research reported in this thesis explores possible solutions for a STEP compliant information model.

The overall aim of this research is

> "To investigate the requirements for the design of a STEP compliant CAPP/CAM system to generate NC programs for asymmetric rotational parts in a STEP compliant integrated environment"

This thesis is organised in ten chapters as depicted in figure 1.1.

Chapter 1 provides the main introduction of the research work and outlines the structure of the thesis. Chapter 2 presents the aims and objectives of the research and sets the scope. The main background information on CAD, CAPP, CAM and CNC including feature technologies and information models, in the light of the design and manufacture perspectives, is provided in Chapter 3.

Chapter 4 explains the structures of the STEP standard. Chapter 5 describes the new STEP-NC standard. Chapter 6 introduces possible theoretical views for design and implementation of an integrated environment for design and manufacture, together with the author's classification of 3 STEP compliant CAD/CAPP/CAM system frameworks. In Chapter 7 the design of a STEP compliant feature based information system to support process planning is described in respect of one of the STEP compliant frameworks. The merging of information models for milling and turning features and manufacturing operations is described together with a new extension using parts of the STEP standard that supports an experimental prototype. Chapter 8 describes a set of dialogue interfaces for an experimental prototype based on the principles explained in Chapters 6 and 7. It is demonstrated through a case study of a rotational part which underpin the feasibility and raises awareness over a number of theoretical and implementation issues. Chapter 9 raises discussion on the ISO 14649 standard identifies gaps in the standard. It also provides analysis of the proposed frameworks, the main research results and a vision of the future of CNC manufacture. Finally, Chapter 10 reports the research conclusions and discusses further research to build up upon and extend the results. The appendix provides a list of the author's research papers.

Part 1: Introduction and Research Scope

Chapter 1
Introduction

Chapter 2
Research Scope

Part 2: Background and Literature Review

Chapter 3
Review of Computer Aided Process Planning and Manufacturing Using Features and Information Models

Chapter 4
Review of Standards for Information Exchange

Chapter 5
Review on STEP Compliant Manufacturing

Part 3: Theoretical view and System Design

Chapter 6
Frameworks for a STEP Compliant Turn/Mill CAD/CAPP/CAM System

Chapter 7
Design and Specification of a STEP Compliant CAPP/CAM System

Part 4: Experiments and research conclusions

Chapter 8
Realisation of a STEP Compliant Turn/Mill CAD/CAPP/CAM Environment

Chapter 9
Concluding Discussion

Chapter 10
Conclusion

Figure 1.1 – The description of structure of thesis

Chapter 2

Research Scope

2.1 Introduction

This chapter outlines the overall research scope of the work together with aims and objectives. It also establishes and describes the individual areas for the scope of this research.

2.2 Research Aims and Objectives

The integration of the various phases of the design, planning and manufacture chain through the use of computer systems has been a necessity for years with the use of information models being seen as a way forward to integrate the design, planning and manufacturing phases. The use of a neutral standard representation of product, process and resources can facilitate the integration though it is not based on a particular vendor format. The recent development of the ISO 14649 standard together with new parts of the ISO 10303 (STEP) standard opens new avenues to achieve such standardization.

The major barrier for this integration has been the diversity of information and data formats used among the many CAx systems' vendors. The STEP standard was conceived to represent product data models through the whole life cycle. However, the initial parts of this standard were more related to the product itself rather than on how it was manufactured. The recent efforts in the development of new parts of STEP, related to manufacturing features and process planning together with the ISO 14649 (STEP-NC) has opened new avenues for research.

This research work has two hypotheses. The first is that the use of standards to build an information framework should create the conditions for seamless information flow in the CAD/CAPP/CAM/CNC chain. The second is that, for a set of STEP compliant features, the use of the milling and turning models from ISO 14649 can support the interoperable manufacturing of rotational asymmetric components.

The principal aim of this research has been described as "to investigate the requirements for the design of a STEP compliant CAPP/CAM system to generate NC programs for asymmetric rotational parts in a STEP compliant integrated environment". In order to achieve this principal aim, a number of objectives have been identified. Namely:

i. To review the literature relating to STEP standards, CAD/CAPP/CAM/CNC and feature-based research.

ii. To specify CAD/CAPP/CAM frameworks to support STEP compliant NC manufacture.

iii. To investigate and realise a STEP compliant information model to support an integrated CAD/CAPP/CAM/CNC environment for asymmetric rotational parts (ie. Product and Manufacture Models).

iv. To explore the use of STEP compliant features for CNC manufacture of asymmetric rotational parts and to contribute with the STEP community to build a standard for interfacing with the CNC control.

v. To design a computational STEP compliant CAPP/CAM prototype based on (i), (ii), (iii) and (iv).

vi. To demonstrate the capability of the STEP compliant CAPP/CAM prototype through a case study for an asymmetric rotational component.

2.3 Research Scope

The following sections describe the research scope in line with the research objectives listed above.

2.3.1 Review the literature relating to STEP standards, CAD/CAPP/CAM/CNC and features based research

Feature based research has been a major area of work for over thirty years. This enormous body of research will be reviewed and assessed to identify possible methods for its application in relation to STEP features. In addition, STEP standards and other ISO standards, relating to design and manufacture, need to be carefully evaluated in order to form the basis of a STEP compliant framework. Thus a literature review in these two areas is an important basis for the author's research.

2.3.2 Specification of a framework to support STEP compliant NC manufacture

Based on the input from 2.3.1, a STEP compliant CAD/CAPP/CAM framework will be developed to identify the functional and operational requirements for STEP compliant NC program generation of asymmetric rotational components. The use of systematic design methodologies (e.g. IDEF0, IDEF3, EXPRESS-G and UML) will be utilised to define the framework and the STEP compliant information model supporting structures.

2.3.3 To investigate and realise a STEP compliant information model for asymmetric rotational parts

This work will identify STEP compliant product and manufacturing data models to support the ISO 14649 turning and milling standards. The work will identify a generic manufacturing model structure to represent turning centres which will be based on the previous research models developed in Loughborough University (Molina 1995). A major difference and extension will be the need to represent STEP compliance. In addition, product and process data models will also be specified and developed to represent ISO 14649 for asymmetric rotational components. The use of parts of ISO 10303 will be attempted in order to achieve a higher level of integration as a standard representation of information can lead to easier data and information exchange and sharing.

2.3.4 Explore the use of feature technology with a STEP compliant approach

This research will explore the use of STEP compliant turning and milling features to represent rotational components. The research will investigate how these features can be used for such components, together with appropriate representation product and manufacture information models. In addition, collaboration with the major players in the development of ISO 14649 should be established to ensure that this research is fully aware of the progress and developments in the standards. In addition such collaboration will also provide opportunities to contribute in the construction of the standard.

2.3.5 Realisation of a STEP compliant CAPP/CAM computational prototype

In order to test and validate the results of this research there is a need to design and specify an experimental computational prototype that uses the knowledge achieved in the objectives 2.3.3 and 2.3.4. Based on the framework mentioned in 2.3.2 an initial computational view point will be developed for the components as identified in 2.3.3.

2.3.6 Demonstration (Component) verification

Once built, the prototype must be verified for a rotational component. This will be achieved using an example part with typical rotational features and additional milling features. In addition to testing the prototype this example component will verify the STEP compliant information models identified in 2.3.3 above.

Chapter 3

Review of Computer Aided Process Planning and Manufacturing Using Features and Information Models

3.1. Introduction

This chapter outlines the historical origins of Computer Aided Design(CAD), Computer Aided Process Planning (CAPP), Computer Aided Manufacturing (CAM), Computer Numerical Control (CNC) and the development and state of art of these technologies. The chapter is divided in five major parts, which are related to CAD, CAPP, CAM/CNC, Features Technology and Information Models.

3.2. An Overview of Computer Aided Design

Although CAD is not the focus of this work, it is a closely related discipline for CAPP and CAM systems and for Features Based Design and Manufacture. The beginning of CAD can be attributed back to the work developed by the pioneer Ivan Sutherland that shows the prototype SKETCHPAD in 1963(Bedworth et al. 1991). Since then the design activity has moved from the paper based drawing to two dimensional CAD systems and evolved to the three dimensional systems where more realistic representation and analysis can be realised. CAD models have been used as input for the manufacturing process either for CAM systems or CAPP systems. During the evolution process 3D CAD was developed using wireframe, surface and solid models. These types of models are discussed briefly below.

3.2.1 Wireframe Models

Wireframe models are based on lines (straight or curved) and points to construct 3D models. They are the logical extension of the earlier developed two dimensional CAD systems. However, the limitation of these models are manifold and with no information on surface representation, which causes serious problems of ambiguity in representing real objects (Zeid 1991, Bedworth et al. 1991).

3.2.2 Surface Models

This approach is an improvement from the wireframe models as they use lines and points as the basis to create the surfaces. They provide some use in CAM systems as a surface can be used to drive the tool path from a milling machine and a wireframe model can not. It is however limited and brings some ambiguous representations such as the definition of which object's surfaces defines its object volume(Zeid 1991). Today some product commercial systems still use surface models but with an hybrid approach using solids to describe sculptured surfaces (Delcam 2004, Bentley 2004).

3.2.3 Solid Models

Solid models have the attribute of completeness and unambiguity as a result of the data held in their data base. This makes them a more suitable means to represent geometries for design and manufacturing of products. There are a number of techniques that can be used for solid modelling such as Pure Primitive Instancing (PPI), Spatial Occupancy Enumeration (SOE), Cell Decomposition (CD), Sweeping (S), Constructive Solid Geometry (CSG) and Boundary representation (BRep) (Bedworth et al. 1991). It is recognised that there is an other technique termed Destructive Solid Geometry (DSG), but it can be considered as a sub set of CSG where only the Boolean operator difference is used (Shah 1991, Hounsell 1998). As the Geometric Solid Modellers (GSM) brought a better form to represent the geometries of a product they were still far from solving the problem of design and manufacture. Amongst other problems Hounsell(1998) recognised that GSM systems have some limitations such as:

- difficulties in interpreting geometric information from the manufacturing point of view,
- difficulties in providing non-geometrical information needed for process planning,
- difficulties to distinguish between essential shape information used by the application from the non-essential aspects,
- traditional primitives are not convenient for defining geometric tolerance and manufacturing specifications, and
- difficulties in integrating CAD with other activities such as CAPP and CAM.

As a consequence of these limitations, the research in the area of Feature Based Modelling flourished over the last three decades (Allada and Anand 1995, Salomons et al. 1993, Case and Gao 1993).

3.3. An Overview of Process Planning

One characteristic of the human being is the capacity to think ahead, imagine the future and plan ahead. Since ancestral humans have had planning activities in hunting, fishing, agriculture, trading and in the daily life. In a more generic sense "planning can be viewed as the activity of devising a means to achieve desired goals under given constraints and with limited resources" (Ham and Lu 1988). In manufacturing the planning activity can be seen as the link between design and manufacturing activities (Chang and Wysk 1985, Zeid, 1991). The literature shows many titles related to process planning and is defined in many different ways such as manufacturing planning, process planning, process engineering and machine routing (Chang and Wysk 1985, Chang et al. 1998). The standard ISO10303-49 (1998) defines a process plan as "the sequence of processes required to realize or produce a given product". In fact, it should be seen as an act to create the instructions to produce a part. In the instructions the processes, parameters, machines and tools are selected to transform material from the initial (raw) material in a part according to the design information. According to Ham and Lu (1988), Process Planning includes:

- selection of machine tools
- selection of tools sets
- selection of set-ups
- selection of machine operation and their sequence
- selection of cutting tools
- design of jigs and fixtures
- calculation of cutting conditions
- determination of tool paths
- NC part program generation.

Process planning can be achieved with computer support (Computer Aided Process Planning) or manual (Manual Process Planning). The significant use of features in process planning is recognised by the author but is described in section 3.5 which is related to features.

3.3.1. Manual Process Planning

Most metalworking industries still use the manual process planning. It is human based and relies on the experience of the process planner and/or data handbooks. The former maybe based on the company's knowledge or open source such as the Machining Data Handbook (Machinability Data Center 1980). It is a knowledge intensive activity.

3.3.2. Computer Aided Process Planning

In order to help the process engineers computers can be used to support the process planning task. Computer Aided Process Planning(CAPP) is usually divided into a Variant Approach, Generative Approach, Hybrid or Semi-generative solutions. A comprehensive survey on CAPP systems was performed in the early 1990's by ElMaraghy and colleagues (1993). The importance of models and standards for the integration role of CAPP systems was noted and both will be subject for further analysis in this research work.

3.3.2.1 Variant Approach

This approach is based on storage and retrieval of standard process plans, it is also termed retrieval type process planning (Groover and Zymmers 1984). It uses the similarities among the parts to create the so called families (Chang and Wysk 1985, Zeid 1991, Chang et al. 1998). The similarities may be geometrical or of the processes to obtain the parts. The variant approach relies heavily on Group Technology(GT) that is the technology that suggests that parts with similarities should be manufactured together, using similar machines and operations. These principles were suggested in the 1920's but were wide spread later by Mitrofanov (Varvakis 1991).

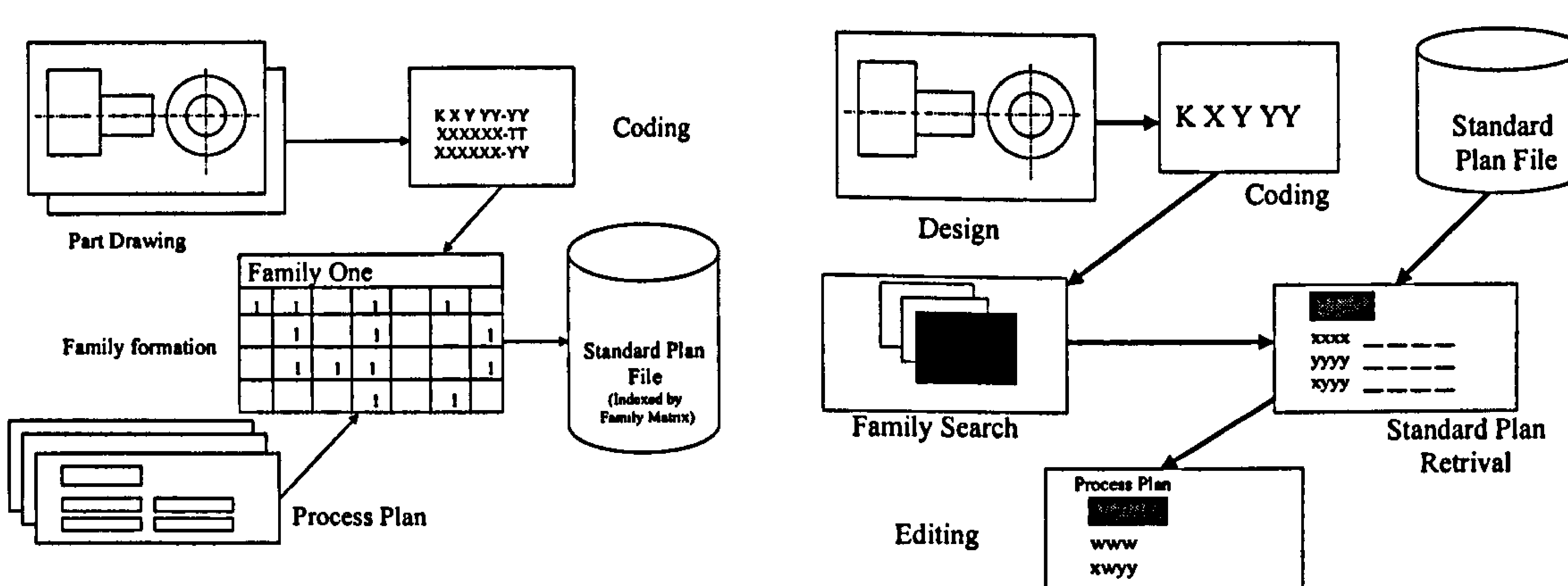
The ISO 10303-240[1] defines GT as :

> "a manufacturing philosophy in which similar parts are identified and grouped together to take advantage of their similarities in manufacturing and design."

The role of GT in the variant approach is the use of codification systems which are used to encode the characteristics of parts. There are two different approaches for GT, one is based on the characteristics of the part and the other on the manufacturing process flow (Pai and Lee 2001). Recently new techniques have been used to improve the use of GT, such as the use of neural networks (Pilot and Knosula 1998) and fuzzy logic (Pai and Lee 2001) for part-machine grouping and classification.

Thus, the work of a variant CAPP system is divided into two stages (Chang et al. 1998) as depicted in figure 3.1

a) classification and codification of parts, so called the preparatory stage.
b) retrieval and editing of process plans , called the production stage.



(a) Preparatory Stage (b) Production Stage

Figure 3.1 – The Preparatory and Production stages in Variant Process Planning adapted from(Chang and Wysk 1985)

[1] ISO 10303-240 is described in Section 4.6.2

3.3.2.2 Generative Approach

In the generative approach no standard plan is necessary. The system uses information about the part such as geometry, tolerances, surface finish and knowledge about the machining process machines (Rembold et al. 1993) to create the process plans. Therefore, for each new part a new process plan is created, or in the jargon "generated" from the information and knowledge which are captured in many different forms. The current trend on parts' information uses features to describe the parts (Yuen et al. 2003, Paris and Brissaud 2000). Many techniques can be found in the literature for capture, representation and use the knowledge used in generative systems. Shin et al. (2003) developed a specialised generative integrated CAD/CAPP/CAM system for machining die patterns.

3.3.2.3 Hybrid and/or Semi-Generative Approach

This approach can be seen as an advance from the Variant approach. These systems can identify a part family and then can offer a set of solutions. A second solution is the system that starts with an incomplete plan and than builds up to a complete plan. A third solution is to build a plan using a library of standard processes (Ham and Lu 1988). Examples of hybrid approaches are found in the literature such as in Kruth et al. (1996) that describes a feature based process plan with Non Linear Process Plan (NLPP) capabilities that incorporates various manufacturing alternatives. It is a hybrid as it uses grouping of parts into families as in variant planning and uses a generative method called opportunistic process planning. Irani et al (1995) describes a hybrid system that caters for the problem of sequencing. Chu et al (2000) developed a concurrent CAD/CAPP system called Prototype Based Incremental Process Planning. It uses the approach to create a prototype and modify it continually and uses STEP[2] to define the product model. They claim the approach is generative but it retrieves prototype process plans which is similar to the variant approach.

Chang and Chang (2000) use fuzzy logic and artificial neural networks in a hybrid system that either retrieves plans for similar parts or creates plans for new parts combining generative and variant techniques.

[2] STEP ISO 10303 will be discussed in Chapter 4

3.4. Computer Aided Manufacturing and CNC

As more than 50 years has passed since the beginning of the numerical control technology, this section briefly aims to describe the evolution and present developments in computer aided manufacturing. It also highlights the trends in convergence for CAPP and CAM functionalities.

3.4.1 The foundations of manufacturing support systems

In the early 1950's, Massachusetts Institute of Technology (MIT) was invited by Parsons Corporation to solve a manufacturing problem for the U.S. Air Force. It was for the machining of complex shapes for aircrafts such as helicopters and their missiles. In 1952 the first machine tool (an adapted Cincinnati Hydrotel Milling Machine) with a Numerical Control (NC) was demonstrated at MIT (Zeid 1991, Kief and Waters 1992, Lin 1994, Seames 1995). The basic principles of this class of machine are the electronic control of the axis and tool motion (Zeid 1991). There were many improvements in both hardware and software aspects of NC machines. The first generation used vacuum tubes; the second used improved vacuum tubes, and later solid state technology. The third generation used integrated circuits and Read Only Memory (ROM) that made the controllers able to retain part programs in memory, instead of reading punched tapes as used in the 1st and 2nd generations. This led to the appearance of what is known as Computer Numerical Control (CNC) (Zeid 1991). Other important improvements such as display monitors and editing capacity came later.

The software evolution was also remarkable, from the beginning of hardwired machines with the changing from manual block to block programming, APT (Automated Programming Tool) its adaptation such as ADAPT (Groover 2001), AUTOMAP, COMPACT II, and UNIAPT (Seames 1995) and the extensions of APT such as EXAPT (Young 1994), EXAPT II, and EXAPT III (Groover 2001) to the modern graphic interactive CAM systems.

Today the software and hardware available at machine tools is able to simulate graphically the tool motion, tool life control, and Adaptive Control (AC) for on-line improvement in machining conditions. Currently the trends are towards open architectures such as OSACA

(Lutz and Sperling 1997, Sperling and Lutz 1996, Sperling and Lutz 1997) and OMAC (OMAC 1999) on software/hardware systems that may ease the use of non-vendor proprietary technology. One further industrial development is the application of software controllers, where PLC logic is captured in software rather than in hardware. Such systems for example MDSI CNC architecture provides many opportunities to implement open control capabilities, and is currently finding significant applications in retrofitting to older CNC equipment (MDSI 2000).

3.4.2 Current trends in Commercial CAM systems

Although the development in CAM systems has been remarkable there are issues that continue to be unresolved. From the author's point of view the problem of manufacturing integration is still an open field for research. Currently many commercially available CAM systems are based on features technology. The main trend that could be identified is that some are integrated CAD/CAM systems such as CATIA (Dassault 2004), UNIGRAPHICS (UGS 2004) Pro/Engineer (PTC 2004) and others are CAM systems that work either coupled with another CAD system such as EdgeCam (Pathtrace 2005) or systems which have some CAD facilities and import other CAD geometries such as an input for the CAM process namely PEPS (CAMTEK 2004) and ESPRIT (DPTechnology 2004). Feature recognition is one other capability found in some of the last generation commercial CAM systems such as CATIA, ESPRIT and EdgeCAM. Many of these systems have support for tooling such as tool libraries. With these facilities, the user can perform the creation of programs based on the machining of a given set of features, and then generate a post-processed NC program code. It is important recognise that these characteristics bring to these systems some of the functionalities from CAPP. However, the role of integration that is played by CAPP systems is not totally fulfilled by these advances.

3.5. Overview of Feature Technology

Feature technology has been a research theme since the 1970's and since then a number of different uses and approaches can be found in the related literature. As one of the STEP-NC concepts is based on feature description, the aim of this section is to explain about feature concepts and how features are used in design and manufacture. Additionally the more common features for some kinds of parts such as prismatic, rotational and asymmetric rotational parts are highlighted. Figure 3.2 depicts some of the typical features found in prismatic parts.

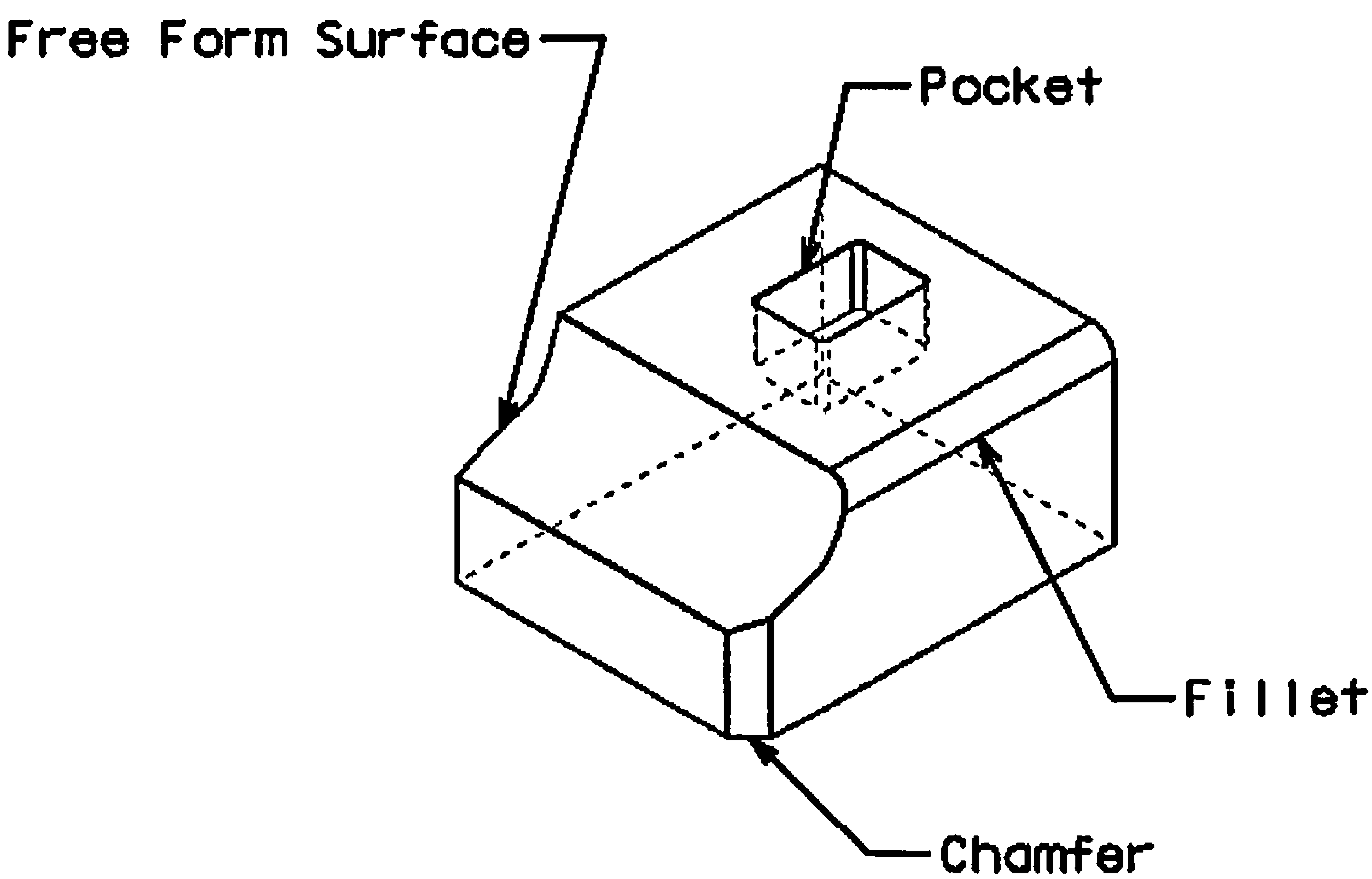


Figure 3.2 – Features found in prismatic parts

3.5.1 Features Concept

The feature concept is not a new idea with the earliest work in this area dating back to Grayer's PhD dissertation dated from 1976 (Shah et al. 1994). Even though there is no consensus about the definition of a feature (Allada and Anand 1995) many authors have commented about the variety of definitions (Hounsell 1998, Varvakis 1991, Shah et al. 1994). According to Allada and Anand(1995) the term feature is derived from the Latin word *Factura* that means the act of making or formation (CAM-I 1981, referred in Allada and Anand 1995). The following is a collection of some expressive features definitions that can be found in the literature.

In most definitions, features are "considered as entities which are of a semantically higher level than the pure geometric elements typically used in solid modelling" (Shah et al. 1994).

"Features represent shapes and technological attributes associated with manufacturing operations and tools" (Grayer 1976 referred in Hounssel 1998 and Shah 1991)

Features are "basic shapes attached together for functional or manufacturing reasons. Even though features are parts of the structure of a component, they cannot physically stand alone, they must always be associated with others to constitute components or more complex features" (Borja 1997)

"A feature is a region of interest on the surface of a part" (Pratt and Wilson 1985).

"The essence of the feature concept is that a product description not only says what the product is, but also contains implicit and explicit information on how it may be transformed to or from some other state" (Case 1992).

Bidarra and Bronsvoort (2000) define a feature as "..a representation of shape aspects of a product that are mappable to a generic shape and functionality significant for some product life-cycle phase" (Bidarra and Bronsvoort 2000).

The AP 224[3] (ISO10303-224 2000) does not define explicitly a feature but, in section 4 of this Application Protocol the Unit of Functionality (UoF) manufacturing feature (*manufacturing_feature*) is described as follows "...contains the information necessary to identify shapes which represent volumes of material that shall be removed from a part by machining". The ISO 10303-224, named AP224, is concerned on machining features and that is reflected in the definition.

[3] AP224 is described in detail in Chapter 4 Section 4.6.3

3.5.2 Features Classification.

As with feature definitions there are also many features classifications. Takavoli (1993) shows one classification (Tavakoli 1993) and a long list of features types is found in Hounsell (1998).

Bhandarkar and Nagi (2000) classified features as:

- Form features : which identify the combination of geometric and topological entities in such a way that it makes a practical sense during the various stages of a product life-cycle;
- assembly features : which assist in the easy location/mating of parts for assembly;
- material features: which specify material composition and condition information such as properties /specifications or treatment applied to material and surfaces;
- tolerance features : such as geometric tolerances or surface finish; and
- functional features: such as performance parameters, operating variables or design constraints.

Hounsell (1998) when describing form features defends that: "however, each form feature could have a set of possible manufacturing processes for obtaining the desired shape (a *hole* could be *drilled, bored* or *punched*). If such a strong geometrical and technological inter-relation drives the vocabulary used to deal with form features, then they are called manufacturing features". This means that manufacturing features may be considered a particular case of Form Features.

Work related to feature taxonomies is available in Tavakoli (1993), Varvakis (1991), and in Case and Harun (2000) where the robust approach of the Gindy's feature taxonomy of EADs (External Access Directions) is highlighted (Gindy 1989). When form features represent shapes obtained by swept volumes of tool cutting paths they are sometimes called machining features (Young and Bell 1993). Manufacturing features are also divided by the type of operation such as: prismatic for shapes produced by extrusion, milling, drilling and similar processes, rotational form features also called turning form features are related to products with axial symmetry. Sheet-Metal form features refer to bending, forming and punching processes, casting or moulding form features model investment casting, forging, injection moulding and similar processes and sculptured form model complex curved surfaces (Hounsell 1998).

3.5.3 Features Benefits

There are many benefits in the use of feature based approaches. Varvakis (1991) and Tavakoli (1993) highlight some of these, but they also can be found in Chung et al.(1988):

- users can express easily the design intent by manipulating features directly, this approach eliminates the tedious intermediate step,
- feature data-bases allow reasoning systems to perform heuristic optimisation of manufacturing analysis, and
- features can contain knowledge to facilitate NC machine programming, process planning and automatic Finite Element Meshing.

3.5.4 Feature Based Approaches

The literature shows three main approaches to use features namely: human feature recognition (Allada and Anand 1995, Shah et al. 1994), design by features and automatic feature recognition (Allada and Anand 1995, Shah et al. 1994, Yuen and Patri 1999) also called feature extraction (Jain and Kumar 1998, Prabhu et al. 2001).

3.5.5 Human feature Recognition

In this approach the user interacts with the system identifying the presence of features in the part model (Jha and Gurumoorthy 2000). This task is difficult in nature, and in addition this approach is generally recognised as being inefficient (Allada and Anand 1995).

3.5.6 Design by Features (DBF)

In this approach the user constructs a model using features as "construct blocks", it is also known as a Top-Down approach (Shah et al. 1994). Normally in the DBF approach there is a set of features intended to represent the designer's needs and a vocabulary for the type of component being modelled. Figure 3.3 shows the interaction between the user and Design by Feature System.

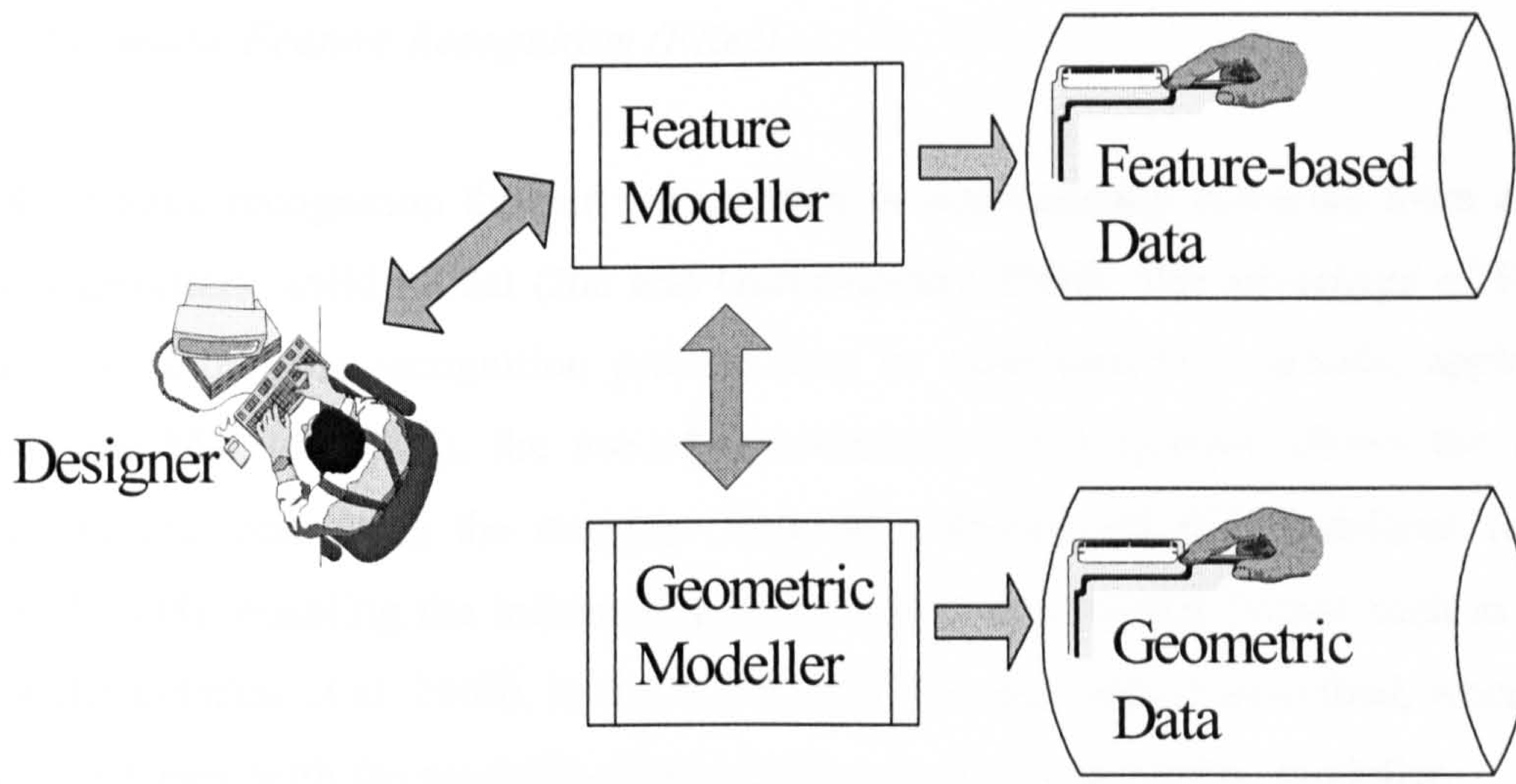


Figure 3.3 - A Design-by-Features (DBF) System Approach (Hounsell 1998).

Some advantages that may be highlighted in this approach are identified by Hounsell (1998):

- a great variety of non-geometric information can be stored and manipulated in addition to the geometry itself (Laakko and Mantyla 1993);
- the use of a more natural design language, closer to the designers expertise, is used to improving the design's effectiveness;
- the use of a set of features available helps standardisation; and
- can ease the integration with design related tools and other applications, such as CAPP and CAM. (Hounsell 1998):

One shortcoming addressed in the literature is the way that most of the commercial systems handle features. They use a history-based approach, which is dependent of creation sequencing and relationships and suffer from a lack of meaning (Bidarra and Bronsvoort 2000). Bidarra and Bronsvoort suggest a semantic feature modelling approach where feature specification and the model maintenance are separated and stored in a declarative model; therefore the features semantics are well defined (Bidarra and Bronsvoort 2000). However the main drawback exposed in the literature is the restriction of a pre-defined set of features that restrain the creativity of the users of these systems (Shah et al. 1994, Hounsell 1998, Allada and Anand 1995).

3.5.7 Automatic Feature Recognition (FRec)

With the feature recognition the part information is automatically extracted from a given part in a geometric solid model (Jha and Gurumoorthy 2000). The advantage of Feature Recognition is that the recognition process may be optimised to a specific application (Laakko and Mantyla 1993), the use of conventional CAD systems allows the use of features without restricting the designer team to a limited set of pre-defined features (Hounsell 1998), enabling the information to be stored in a neutral format such as STEP AP 224 (Bhandarkar et al. 2000). In figure 3.4 the FRec approach is described, when there are two databases, with the modelling being achieved using a geometric modeller.

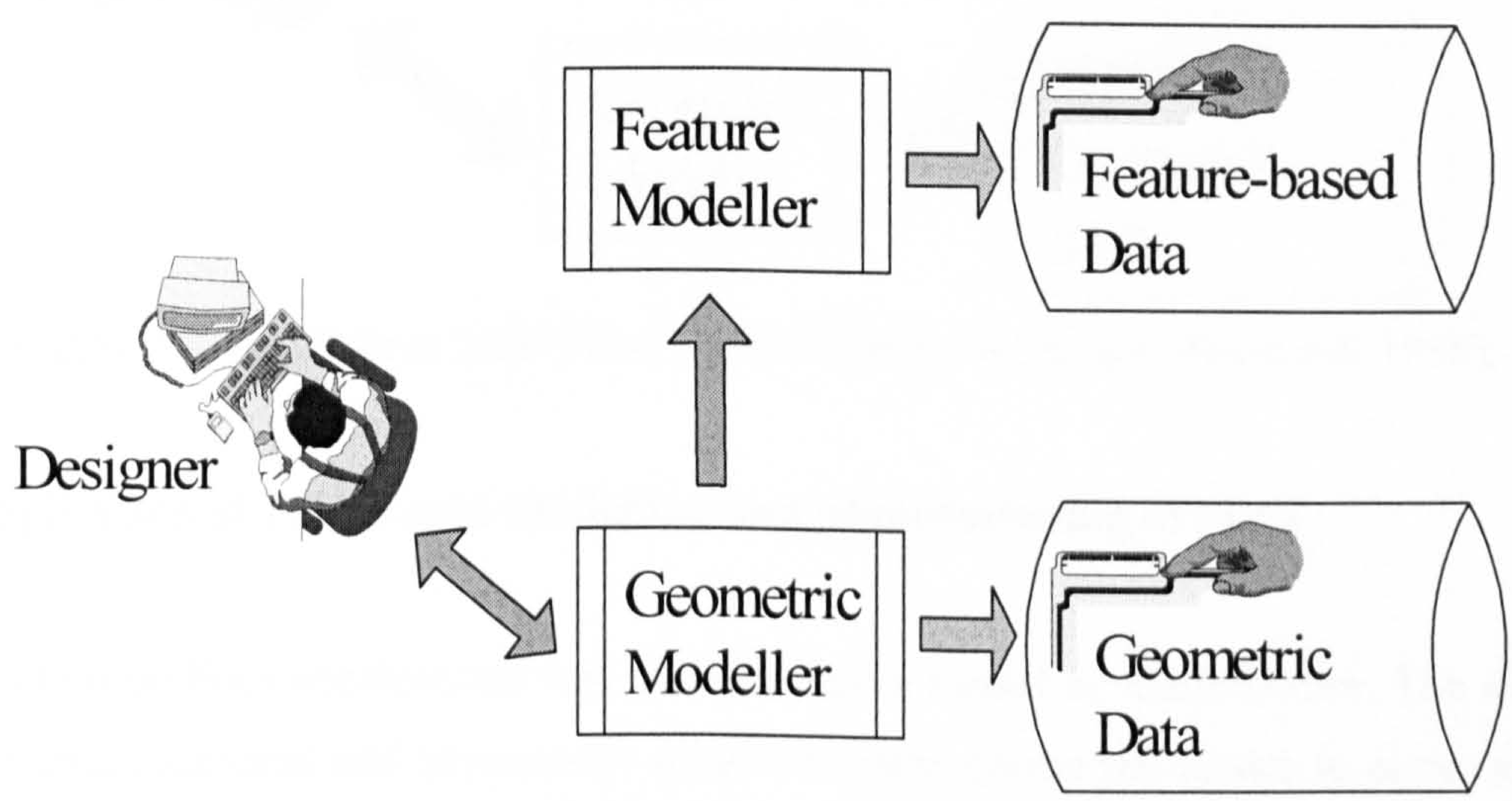


Figure 3.4 - A Feature Recognition (FRec) System Approach. (Hounsell 1998)

The main drawbacks of this approach are: difficulties of working with very specialised features (Shah et al. 1994), feature interpretation is domain dependent (Jha and Gurumoorthy 2000, Jha and Gurumoorthy 2000a), the design intent is not captured at the beginning and the techniques restrain the method (Tavakoli 1993), and the process of extraction and recognition may be time consuming (Allada and Anand 1995).

3.5.8 The Hybrid Approach: Design-by and Features Recognition (HDR)

In order to take advantage of both, Design by Features and Feature Recognition, and avoid their disadvantages some authors (Allada and Anand 1995, Han and Requicha 1997, Hounsell 1998) address an Hybrid approach. The idea is to use the DBF approach to model the part coupled with a FeR system to extract these features (Shah et al. 1994a). Figure 3.5 shows that the designer accesses both databases to perform the task of design and to recognise features for a given process.

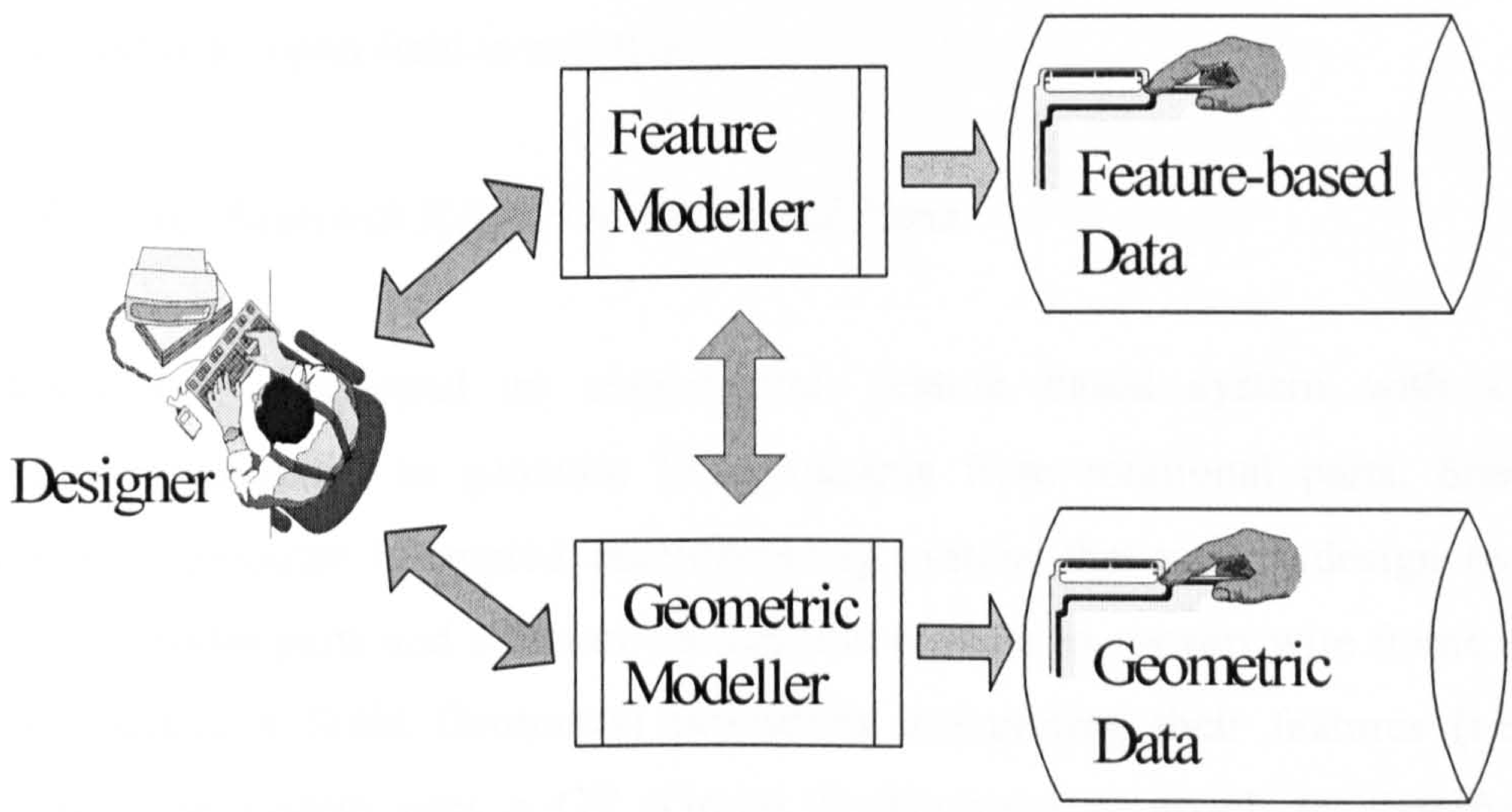


Figure 3.5 – A Hybrid DBF/FRec (HDR) System Approach (Hounsell 1998).

3.6. Application of Features in Modelling and Manufacturing of Parts

This section outlines applications that use features to model or manufacture. The division of prismatic, rotational and asymmetric rotational parts allows the author to cover most of the areas where features are used in the intent to design, plan and manufacture a part.

3.6.1 Features Related to Prismatic Parts

Jain and Kumar (1998) use a 2D CAD system to represent prismatic parts for small companies. The system uses only 3 features (hole, slot and step) and classifies these by shape such as rectangle, trapezium, and more complex closed profiles. Once extracted the features are used in a Computer Aided Process Planning (CAPP) system.

Bhandarkar and Nagi (2000) developed an algorithm for prismatic solids with plane surfaces produced by milling operations for elementary shapes such as plane surfaces, cylindrical, surfaces, etc. The algorithm works also with complex surfaces such as

NURBS(Non Uniform Rational B-Spline Surfaces). The features are extracted and stored using STEP[4] AP 224.

Jha and Gurumoorthy (2000) proposed a system for prismatic parts that have problems of features interpretation. This is used to maintain the data integrity of the part model in a concurrent engineering environment. Feature interpretation is another issue found in the literature and is an open field to research.

3.6.2 Features Research Related to Rotational Parts

Varvakis (1991) developed an experimental feature based system with a Product Modelling environment to generate NC programs from rotational parts. Sheu (1998) developed a computer integrated manufacturing system that uses a design by features approach to model parts and a feature recognition module to convert wire frame entities to CSG (Constructive Solid Geometry) primitives interpreting their features (i.e. Hybrid Approach). The system uses a GT (Group Technology) approach to classify the part geometry and generate the corresponding process plan to rotational parts.

Devireddy and Ghosh (1999) used a feature based modelling shell to provide information about form and precision features for rotational parts. The modeller system is wire frame based and allows the integration of new features. The model is interpreted by an ANN (Artificial Neural Network) enabling the CAPP system to generate process plans.

Tseng (1999) developed a modular hybrid approach that recognises features from design by features modelling rotational parts. The work utilises the concept of functional modules to design the part. These modules are compound or a set of machining features. As there is a limited number of modules and limited number of features in each module the feature recognition task is simplified.

---

[4] STEP AP 224 (ISO 10303 Part 224) is described in Chapter 4 Section 4.6.2

3.6.3 Use of Features for Asymmetric Rotational Parts

Tavakoli (Tavakoli 1993) suggests a hierarchical solution called a *Feature & Region Schema*, where predefined regions are defined and hierarchical presentations of regions and features are proposed. An experimental system was developed to describe parts using machining features and generate a process plan and NC code. Maziero proposed a system that handles milling features in rotational parts (Maziero et al. 2000). In this category those parts are machined in so-called parallel NC machines. This kind of machine has the following characteristics to (Levin and Dutta 1992, Allada and Anand 1995):

- perform simultaneous operations;
- have functional combinations of operations(for example, turning and milling operation); and
- possess a secondary spindle which can machine the back and the front face of the part;

Shunmugam et al. (2002) describe a method for preliminary process planning to determine features sequence and precedence in asymmetric parts using genetic algorithms. They categorised the features in a hierarchical structure that has: primary features(face, cylinder and cone), secondary features(groove, chamfer, thread and C-axis features). In their structure C-axis features are a radial hole, axial hole, slot and keyway. Figure 3.6 depicts the hierarchical structure for the form features.

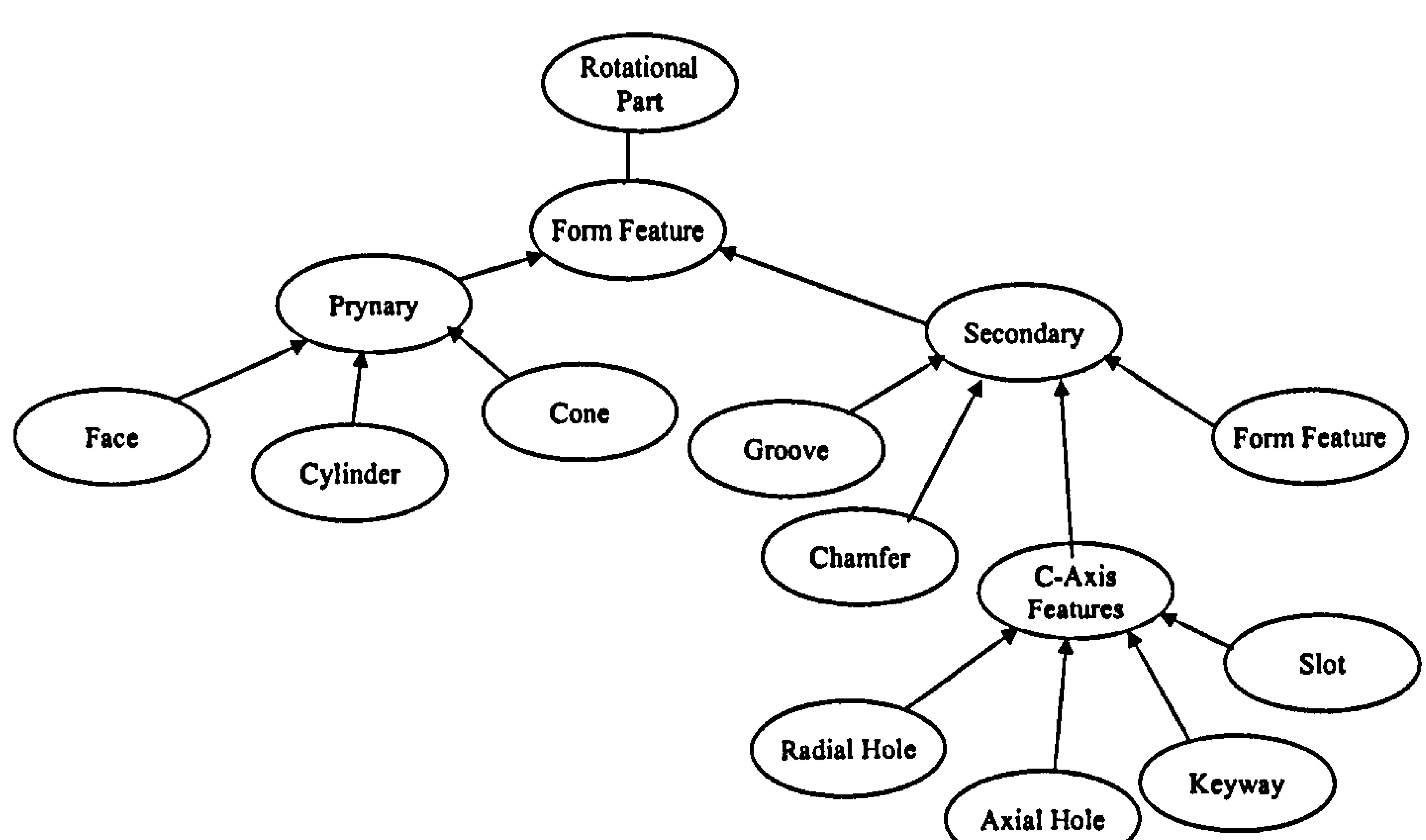


Figure 3.6 – The hierarchical structure of forms features proposed for asymmetric parts (Shunmugam et al. 2002)

The problems related with the turning and milling combined machining is sparsely found in the literature. Among other issues that are not trivial are the sequencing of operation and set-ups (Tseng and Liu 2001) and features interaction.

3.7 Concepts of Information Models

This research work uses the concepts of a Product Model and Manufacturing Model which are types of Information Models. In the ISO10303 standard, information model is defined as a formal model of a bounded set of facts, concepts, or instructions to meet a specific requirement (ISO10303-1 1994) it can also be defined as "a model of information showing relationships between items"(Ellis 1993).

According to Costa (2000) product modelling aims to provide consistent representation of products information, which can be reached and used by one or more software systems during all stages of product design and manufacture.

This is also stated by Fowler (1995) who says that one key characteristic of product information is that it is created, used and added throughout the life cycle of a product. It also highlights the need of information sharing for systems integration which is claimed to be achievable using STEP.

McKay et al. (1996) highlighted that activities such as process planning require more than just geometry, they need product data. They also stressed that a computer representation of product data is composed by two parts: the product data model which is the definition of form and contents of the product data, and the product model which contains the actual data for a particular product.

Product models can be focused on different aspects of the product and then can be defined as different types of product model as identified by Krause et al. (1993) as following:

i) Structure-oriented product models
ii) Geometry oriented product models
iii) Feature oriented product models

iv) Knowledge based product model

v) Integrated product models, which uses all the above approaches

vi) Model standardization using STEP

Molina and Bell (1999) define the manufacturing model as "an information model that identifies, represents and captures the data, information and knowledge describing the manufacturing resources, processes and strategies of a particular enterprise".

The resources are entities such as machines, fixtures, tools, handling devices and others physical elements used to realize the product. Processes are the change in properties of the material, in the case of material removal such as machining, typical processes are turning, milling drilling, reaming etc. In the manufacturing model the strategies represent how the resources and processes are used (Molina 1995). According to Molina(1995) the information can be captured in a four level manufacturing model which are: factory, shop, cell and station.

Zhao, et al. (1999) defined a model, based on Molina(1995) and extended this model to one more level (Enterprise) and use the manufacturing model for virtual enterprises. They use AP 224 to represent features and use the ISO14649-111 (see Section 5.8) to represent milling and drilling tools. Figure 3.4 depicts the 4 and 5 levels concepts of manufacture model.

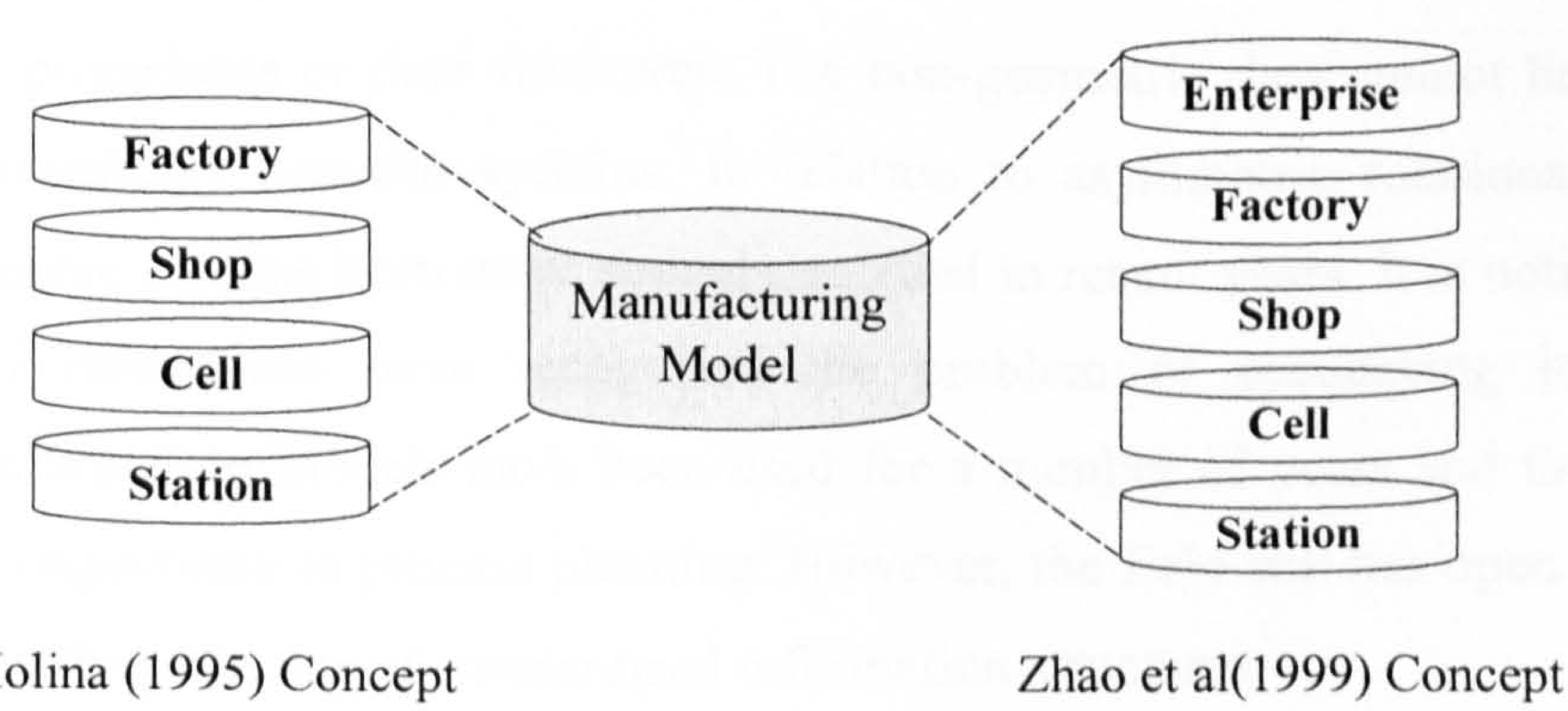


Figure 3.4 – The concepts of 4 and 5 levels for a manufacture model.

The ideas which describe a manufacturing model were created in the context of the MOSES project (Molina 1995, Molina and Bell 2002) in the early 1990's. Further information relating to the MOSES project can be found in (Harding and Popplewell 1996; Mckay et al 1997; Molina and Bell 1999).

Jurrens et al (1995) report a comprehensive resource model using EXPRESS where several industrial partners were involved. Liu and Young (2004) used a manufacturing model together with a product model and an order model to support global manufacturing co-ordination decisions.

Guerra-Zubiaga (2004) defines a manufacturing model based on Molina's ideas and add knowledge classes to represent tacit, implicit and explicit types of knowledge and maps the processes using ISO 14649 part 11 and 12 taxonomies.

3.8 Summary on CAD/CAPP/CAM Systems and information models

This chapter describes the technologies of CAD, CAPP, CAM and Information Models. Although CAD and CAM are stable technologies and feature technology has been researched for decades, the issue of integrating CAD and CAM is still an open field. Suggestions of many types of feature taxonomies are found in the literature, as well as algorithms for feature extraction. Once the operations are created inside the CAM system more technological data is added such as cutting parameters and machining strategies. However, it is necessary to point out that all this work has been undertaken with poor or non standard procedures or data structures. The non-geometric data cannot be shared or exported conveniently between systems. In relation to asymmetric rotational parts the literature is sparse and has been more actively pursued in recent years. It is noticeable that a number of researchers have recognised the problem of sequencing in mill/turn operations. Information models have been used for a number of years and the literature highlights its importance to process planning. However, the field still has open avenues to explore especially in the use of standardised information structures.

Chapter 4

Review of Standards for Information Exchange

4.1. Introduction

The need for data exchange has been a requirement since the first applications of CAD/CAM systems. It has historically and continues to be a process of evolution. This chapter describes the evolution of standards for data exchange for engineering systems. Section 4.2 introduces the various methods for information exchange, Section 4.3 describes early efforts for standardization, Section 4.4 describes the STEP Standard and major entities that form the structure and concepts relating to the standard. The final part of the chapter outlines in more detail the application protocols related to the author's research.

4.2. The Methods for Data Exchange

The advent of Computer Aided Design (CAD) tools represented an impressive gain in productivity over the use of the paper drawings. Not only because CAD tools made it easy to edit and store engineering data as never before but they also enabled the use of information directly from design to manufacturing tools (Goldstein et al. 1998). As fast as new CAD and Computer Aided Manufacture (CAM) tools were created the number of formats to represent and store product data increased as well. This was and is still a problem to companies, which need to share this data between different tools either in their own process or with a partner in the supply chain. This problem was perceived in the early beginning of CAD/CAM systems where two major methods were recognised to solve the problem (Zeid 1991). The first is called direct translation that implies the development of a pair of translators to exchange data between each pair of systems. The other solution is the indirect translation of data using an intermediary file also called a neutral file. The use of a neutral file format implies that each application needs a pair of translators, one to write in, and other to read from the neutral file format. This is a vendor's independent format and its structure is also independent of any existent system (Zeid 1991).

The advantages of direct translation are the small size of the generated files and speed as it is a one-stage solution, and in addition for a specialised company the loss in semantic data is usually low or none. The major drawback is when the number of CAx systems involved increases, the number is so high that many different translators are required and the solution becomes very expensive. Figure 4.1(a) shows the direct translation solution and figure 4.1(b) shows the neutral file strategy solution. The equation 4.1 shows the number of translators needed when there are more than 3 systems involved using direct translators and equation 4.2 is the number of translators needed when using indirect translators (Kern 1997, Zeid 1991).

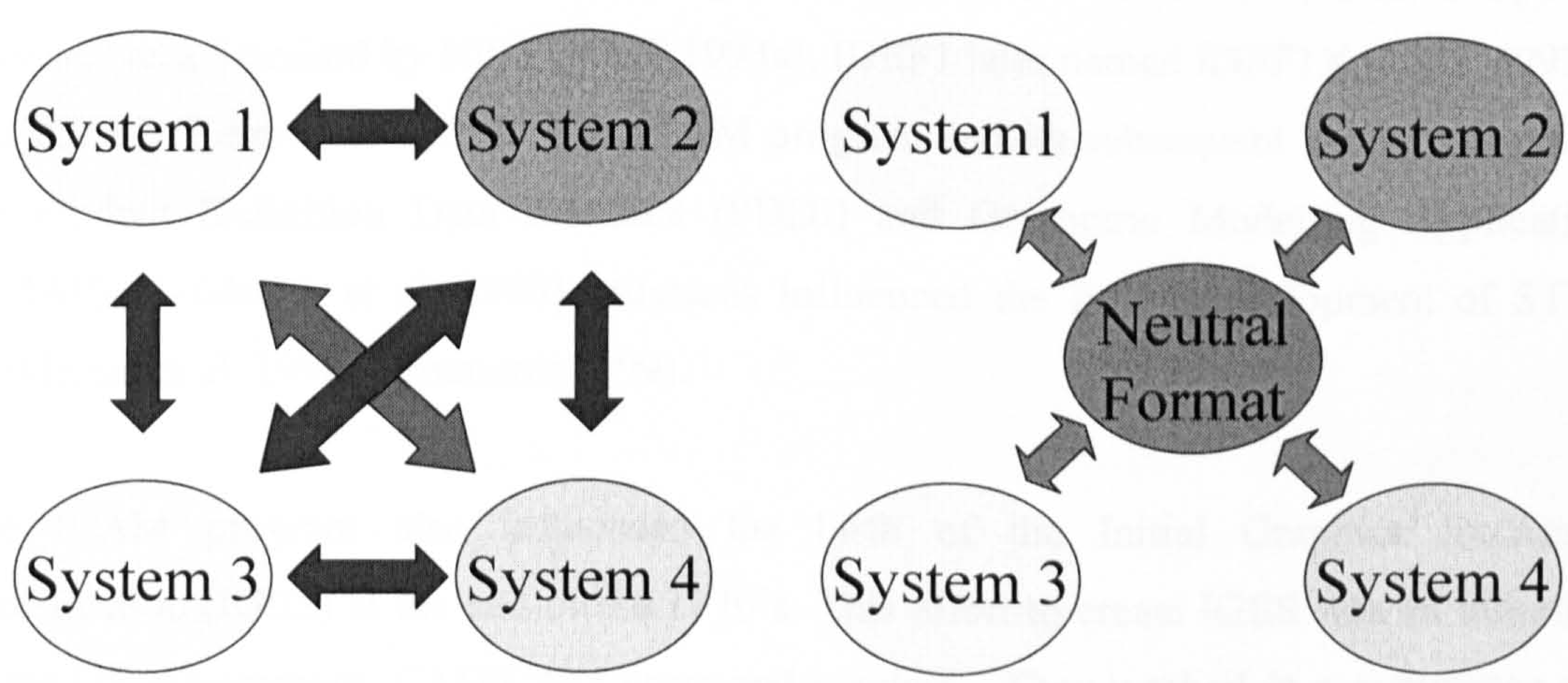
$$N = n \times (n-1) \tag{4.1}$$

$$N = n \times 2 \tag{4.2}$$

Where:

N = number of translators.

n = number of systems.



(a) Data exchange using direct translators. (b) Data exchange using Neutral File.

Figure 4.1 – The ways for data exchange (Adapted from Zeid (1991))

Kern (1997) highlights the advantages of using neutral files as it is necessary to only have two translators for each CAx system involved, independence of supplier, possible use in archiving which protects the user against obsolescence as it is not technology dependent. The author also can say that the cost of development tends to be lower than the cost of direct translators as a consequence of the number of programs necessary when the number of systems grows.

The main disadvantage of neutral files detected by the author is the large size of these files that are normally larger than those obtained in direct translation. A further concern is the loss of information that can occur due to the non-existence of corresponding entities in one of the systems involved.

4.3. Early Standards for Design and Manufacture

The efforts to create a neutral data exchange format began in the 1970's with the contribution of X3/SPARC Committee of the American National Standard Institute (ANSI) in the United States. It proposed a three layer methodology that gives different views of the same information entitled conceptual, internal and external views. This methodology was used by the Integrated Computer Aided Manufacture (ICAM) program to develop the formal methods for information modelling named IDEF0 (ICAM Definition Level 0) later proposed as a Standard by NIST (NIST 1993a), IDEF1 later named IDEF1X (NIST 1993b) and IDEF2 (Kemmerer 1999). The ICAM program and its subsequent contracts such as the Product Definition Data Interface (PDDI) and Geometric Modelling Application (GMAP) (Goldstein et al. 1998) programs influenced the future development of STEP (Goldstein et al. 1998, Kemmerer 1999).

The ICAM program also influenced the birth of the Initial Graphics Exchange Specification (IGES) at the end of the 1970's. This effort to create IGES was an initiative of the US government, CAD/CAM users and vendors. They worked in a committee co-ordinated by the National Bureau of Standards (now the National Institute of Standards Technology-NIST) which generated the first release of IGES in 1980 (Kemmerer 1999). This standard achieved relative success but suffers from some problems that are difficult to solve mainly because of its conception for geometrical and topological representation that was inadequate to represent a product throughout its life cycle. IGES does not have a formal model; there are a number of specific interpretations by the vendors which lead to translations being incomplete or containing errors. IGES uses an 80-column format that is difficult for human reading (Bhandarkar et al. 2000), also the file size and processing time are very large. In order to solve these problems many efforts were made to develop an International Standard. Other contributions in the effort to develop a standard for a data exchange format have been undertaken by the European Association of Aerospace Industries that have developed a format to exchange simple surfaces. This was not extensively used but the United Kingdom generated the AECMA Report of the Geometry Data Exchange Study Group to the International Organization for Standardization (ISO) that provided a useful contribution to today's STEP Standards.

In 1982, the first release of the German Standards VDA (Flachenschnittstelle Des Verbanes der Deutschen Automobilindustrie) for the automotive industry was issued, which addressed the issue of data exchange for free form surfaces and free form curves (VDA-FS) and subsets of annotation entities (VDA-IS). The VDA-FS was a contribution from Germany to the development of STEP. The French contribution comes from SET (Standard D'Exchange et de Transfert) a project of Aerospatiale to bypass some problems of IGES translations. It added detailed specifications to the mechanical area, supplementary information about data structures and concepts employed, together with rules and recommendations concerning specifications to ensure coherence in future developments (Zeid 1991).

In 1984, a project called CAD Interfaces (CAD*I), funded as an ESPRIT project by the European Commission, focused on product model data exchange and on a data exchange for finite elements analysis. CAD*I used schemas based on a modelling language with much of the shape modelling capability of today's STEP standard coming from CAD*I project (Kemmerer 1999). In the same year during a meeting of the IGES Organization Edit Committee, the effort for the first Product Data Exchange Specification (PDES) began. PDES was proposed by the United States to ISO TC 184/SC4 (Technical Committee 184/Subcommittee 4) and has become the basis to what today is known as STEP.

As can be observed, STEP is a result of the efforts of many organizations in the attempt to develop a method for data exchange and later, data sharing. In the following section the standard is described, as it is the basis for the STEP-NC, which is one of the main subject areas of this research.

4.4. The STEP Standard Concepts and Structure

The set of documents that forms the ISO 10303-series standard is commonly called STEP this is an acronym for the STandard for the Exchange of Product data model. As seen in the previous section, STEP is the result of the experience gained by the community of users and developers of standards through the initial efforts standards for standardising data exchange. The concept of STEP is that it can be used for data exchange and sharing of product information (Fowler 1995). The objective of this standard is to provide a mechanism to describe the product data throughout the complete life cycle (Rahimifard and Newman 1996). An important aspect of STEP is its extensibility, which was one of the initial objectives in the beginning of its creation (Kemmerer 1999). The extensibility is achieved through the use a formal language for modelling data (Loffredo 2000). According to Ashworth and colleagues (1996), among the aims of STEP are completeness and correctness, minimality, understandability, manageability, maintainability and upward compatibility. This is achieved using the strong concept of formal languages, which is applied using the EXPRESS language. This was also the way used to avoid ambiguities in the representation of product data models. As Fowler (1995) points out, one of the key differences between STEP and other standards is the independence of data models defined in the standard and the various ways to implement them.

4.4.1 Structure of the Standard

STEP was structured to be able to describe products of various domains and to test if the applications built using the standardised methods are really adherent, or not, to the ISO 10303 standard.

The structure of this Standard is described in ISO 10303 Part 1 (ISO10303–1 1994) as below:

a- Description Methods : Parts 11 to 19
b- Integrated Resources that are divided in:
   - Generic Resources: Parts 41 to 99
   - Application Resources: Parts 101 to 199
c- Implementation Methods: Parts 21 to 29
d- Conformance Testing and Methodology: Parts 31 to 39

e- Application Protocols: Parts 201 to 1199

f- Abstract Tests Suites : Parts 1201 to 2199

Although, Loffredo(2000) shows this in a more high level structure, which divides the Standard into two parts, namely Infrastructure and Information models as depicted in figure 4.2. The following sections describe the mentioned parts and their functions in the standard.

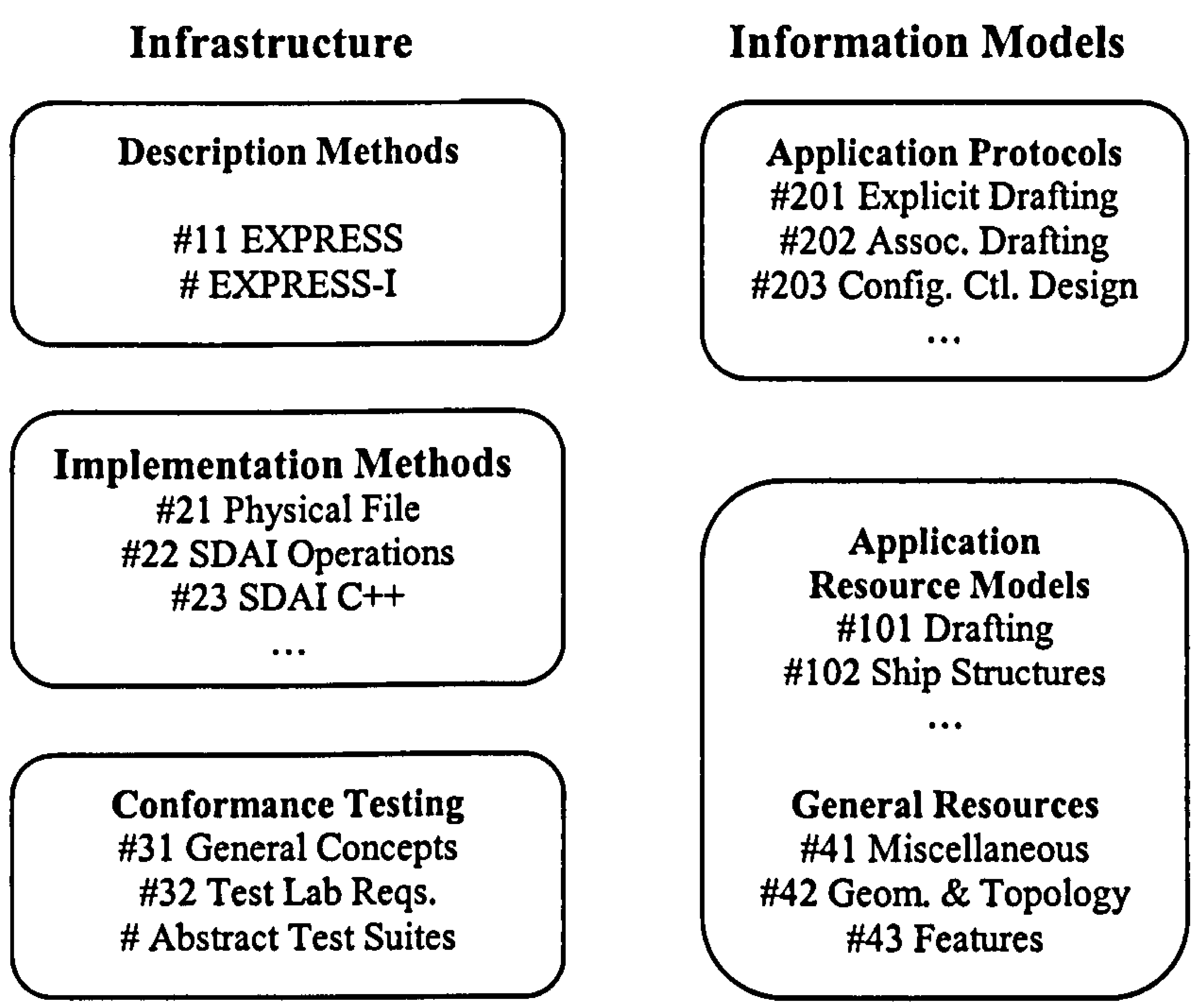


Figure 4.2 – The High Level Structure of STEP (Loffredo 2000)

4.4.2 Description Methods

These methods are based on the idea that the description of product data should not be ambiguous, and the best way to avoid ambiguities is through the use of a Formal Data Specification Language. In order to describe a product using integrated resources and application protocols, the EXPRESS language and graphical presentation of models are used that will be described in section 4.5 (ISO-10303-1 1994).

This part of the STEP Standard (so called 10's Series) comprises of documents relating to languages, which represent product data in a standard form. The fundamental description method of STEP the EXPRESS Language is described in this series (Kern 1997).

4.4.3 Integrated Resources

There are two groups of integrated resources namely the generic and application resources. They comprise of the series 40 and 100 respectively. They are used to describe products using EXPRESS. The generic group are independent resources and can reference each other, the application resources however, cannot reference each other (ISO10303-1 1994). Ashworth et al. (1996) emphasises the key role of these resources. The generic resources provide a flexible means to create integration across different applications, where integrated resources roughly act as building blocks for many other parts of STEP.

4.4.4 Application Protocols

This is the part of the STEP Standard that specifies an Application Interpreted Model (AIM). These models satisfy the scope and information requirements for each application (ISO10303-1 1994). Each AP(Application Protocol) is specific to a particular engineering domain. Application protocols like information models describe the data structures and constraints for a product model (Loffredo, 2000). In fact, the idea of AP's comes from the experiences learned in the IGES/PDES development group (Goldstein et al. 1998, Kern 1997). A description of the main application protocols related to this research are provided in section 4.6.

4.4.5 Implementation Methods

This part of the standard specifies a technique used by computer systems to exchange product data that is described using the EXPRESS language (ISO10303-1 1994). Implementation methods in STEP are also called 20's series. Its function is the mapping of formal specifications to a representation using formal methods used in STEP (Nell 2000). At the time of the writing of this work the following parts have been released(ISO 2004):

- Part 21 - clear text encoding that is used to write exchange files.
- Part 22 - standard data access interface (SDAI).
- Part 23 - C++ language binding to the standard data access interface.
- Part 24 - C language binding of standard data access interface.
- Part 27 - Java TM programming language binding to the standard data access

interface with Internet/Intranet extensions(ISO/TS10303-27 2000).

- Part 28 - XML representations of EXPRESS schemas and data(ISO/TS10303-28 2002).

Particular attention should be given to part 21 which is heavily utilised as it is used to represent the format of most of the interchange files. The last two parts 27 and 28 are currently receiving significant attention of many research groups due to the increased applications on the Internet(Xu and Mao 2004, Proctor et al. 2002, Burkett 2001, Ma et al. 2001, Lee et al. 2003).

4.4.6 Conformance Tools

One of the remarkable features of the STEP standard is the provision of a framework of conformance tests. The conformance tests are developed for each AP and are specified in a abstract test suite (ISO10303-1 1994). The STEP standard places a very high emphasis on tests and is probably unique to place conformance test as part of the standard (Nell 2000). This was one of the major failure points in the former standards such as IGES, SET and VDA (Kern 1997), and was an "open door" for each vendor to design its applications using specific interpretations. The ISO TC 184/SC4 (Technical Committee 184/ Subcommittee 4) committee included the conformance tests from the experience of ISO 9646, the conformance tests methodology for the OSI (Open Systems Interconnection) protocols (Fowler 1995, Kemmerer 1999).

4.4.7 AAM - Application Activity Model

An Application Activity Model (AAM) is a type of model used in the STEP standard to describe an application in terms of its process and information flows (ISO10303-1 1994). It is a graphical model, which depicts the industries activities that supports each AP. A mapping table is used to describe how the information requirements are satisfied (Borja 1997). Figure 4.3 depicts the basic notation of an Application Activity Model in IDEF0 according to the NIST document (NIST 1993a).

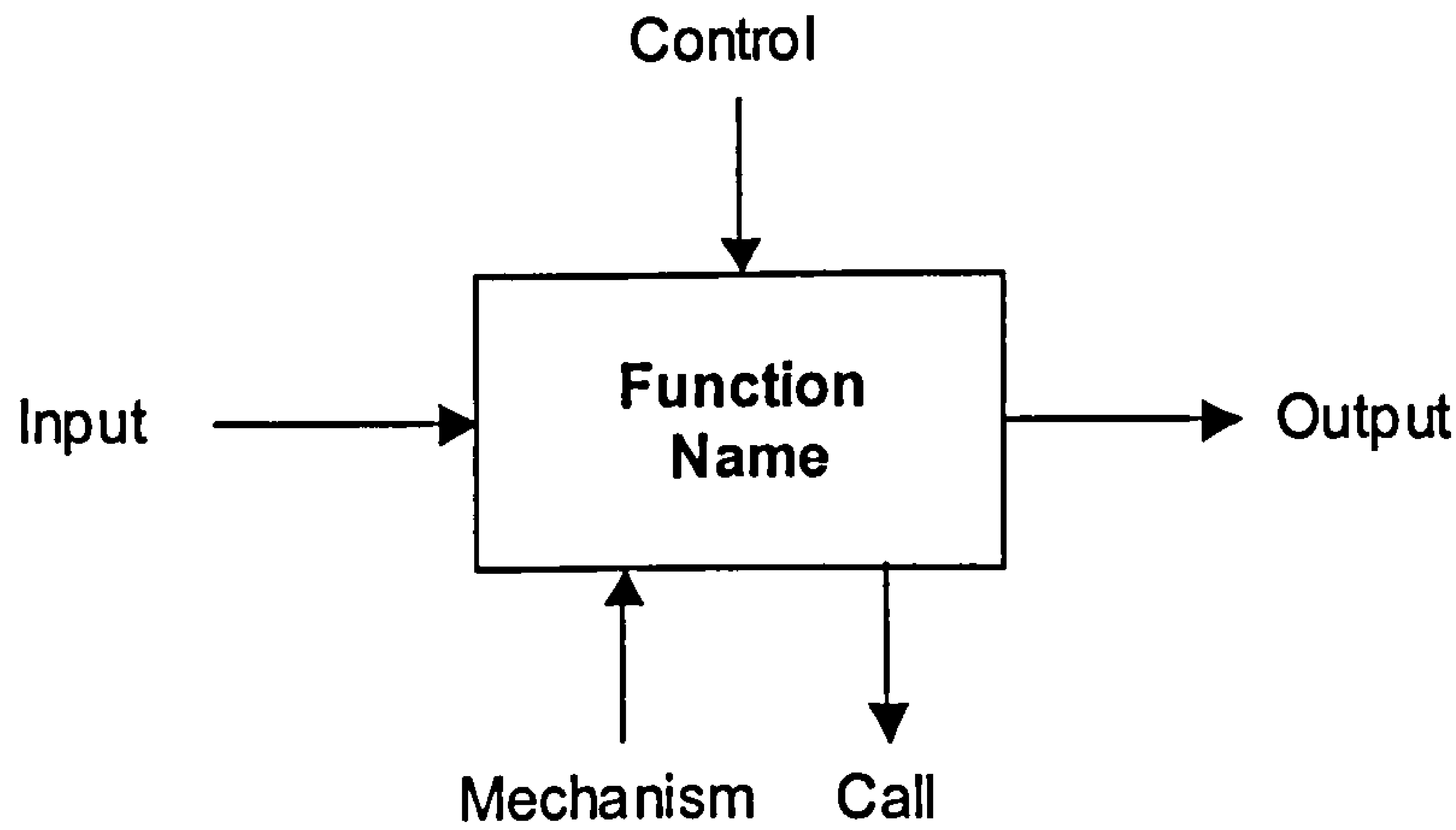


Figure 4.3 – The basic notation of AAM based on IDEF0(NIST 1993a).

4.4.8 ARM - Application Reference Model

In ISO 10303 Part 1, an Application Reference Model is defined as "an Information Model that describes the information requirements and constraints of a specific application context." (ISO10303-1 1994)

This means that for a given AP an Information Model called ARM should be defined. The ARM is a graphical model of entities and relationships that specifies data for an Application Protocol (Borja 1997). The information of a process identified in an AAM must be defined in the ARM representation. The way to define graphically the information in an ARM form is using IDEF0, IDEF1X, NIAM (Nijssem Information Analysis Methodology) information modelling and EXPRESS-G (ISO10303-1 1994, Kern 1997).

4.4.9 AIM - Application Interpreted Model

An AIM is an information model that describes data with names and structures using STEP terminology. It contains the STEP standard names and structures for the data in a given AP and represents the product data to be shared in a data exchange environment in terms of the STEP standard (PDES 1997). It uses a mapping table to describe how the information requirements (ARM) are satisfied (Borja 1997). The AIM is "an information model that uses the integrated resources necessary to satisfy the information requirements and constraints of an application reference model, within an application protocol to be present in a conforming implementation" (ISO10303-1 1994).

4.4.10 AIC – Application Integrated Constructs

Also called the 500's series the Application Integrated Constructs (AIC) are reusable groups of information-resources entities and aim to provide interoperability between AP's. (Kern 1997, Nell 2000). It provides a logical grouping of interpreted constructs to support specific functionality (ISO10303-504 1999). When multiple AP's are in use it is very useful and desirable that information may be shared, an AIC makes it possible to express identical semantics in many application protocols. The concept of reusability that is common in object oriented systems development is used here. This does not mean that an AIC must contain objects as in the meaning used in object-oriented programming but it is object flavoured.

4.5. The EXPRESS Language

The EXPRESS Language is a Formal Data Specification Language defined in the Part 11 of the STEP Standard (ISO10303-1 1994, ISO10303-11 1994). According to Kemmerer (1999) it was designed as a language for communicating information that it has much in common with database definition languages and programming languages but unlike these:

> "...EXPRESS does not confuse the information task with programming or database tasks and it is not specific to a particular programming or database system." (Kemmerer 1999)

In fact EXPRESS is neither a programming language nor a database language. The aim of EXPRESS is to describe the characteristics of information that might exist in an information base (Kern 1997). It uses the Syntax Wirth Notation(SWN), that is based on BNF (Backus-Naur Form) (Wirth 1977) as a basis of the STEP file structure (Kern 1997). The physical file used for exchange of data is defined in Part 21 (ISO10303-21 1994) of the STEP standard and uses EXPRESS to describe the product data. Actually, EXPRESS is the keystone of the STEP standard.

4.6 The standards related to ISO 14649

Within the STEP Compliant approach to program CNC machine tools, the main idea is to share the information about the existing features (see the features concept in Chapter 3) for a mechanical part (ISG 2000b). The application protocol 203 is used to share the general data related to geometry and identification of the part. AP 224 is used to define all the part features, in the early stages of development of ISO14649, AP 213 was thought to support the definition of process planning that splits the features from AP 224 into sets of processes such as milling, turning, grinding and inspection (Step-NC 2000b). However, during the development of this work AP 213 was withdrawn from the development scene and superseded by AP 240. In the case of inspection the use of AP 219 is also being developed (Step-NC 2000b).

The following sections explain the most important protocols used in the research work. These are related to the CAD/CAPP/CAM CNC process chain, namely: AP 203, AP 224, AP 240, AP 219, and AP238

4.6.1 AP 203 - Application Protocol: Configuration Controlled 3D Designs of Mechanical Piece Parts and Assemblies

This AP is well established and has a well-defined scope as cited below:

> "This part of ISO 10303 specifies the integrated resources necessary for the scope and information requirements for the exchange between application systems of configuration-controlled 3D designs of mechanical parts and assemblies. Configuration in this context only includes data and processes that control the 3D product design data. Exchange is used as a scoping consideration to narrow the scope to only those data, which are exchanged as part of the 3D product definition. Organisations exchanging data within the scope of this part of ISO 10303 may have a contractual relationship, the details of which are outside the scope of this part" (PDES 1998, ISO10303-203 1994).

This means that AP203 specifies the exchange of data for mechanical products only. Its aim is to exchange data about the initial phase of the product life cycle while the product is in the design phase. In this specification the 3D shape of a part or assembly may be made by five different types of geometric representation which are: wireframe and surface geometry without topology, wireframe geometry with topology, manifold surfaces with topology, boundary representation and faceted boundary representation (see section 3.2.). These types are also called conformance classes (PDES 1998). The Application Interpreted Model (AIM) is outlined in section 5 of AP 203 where it is identifiable that most of the entities have as source the Parts 41, 43 and 44 of STEP known as the Integrated Generic Resources (see Section 4.4.3), which are shared between other APs. It should be noticed that AP 203 is one of the most used parts of STEP as it is used to import and export files to provide geometric data for a number of CAD and CAM systems.

However the importance of shape exchange, many parts of the AP 203 are dedicated to specify data, which controls the tracking/flow and management of the product. This data includes (ISO10303-203 1994):

- the identification of a product to an organisation's customers and the link of design identification of components;
- documentation of changes and releases of designs;
- the history of the product,
- the structure and relationship of each component of the product to the whole product;
- information concerning materials processes finishes and other design requirements; and
- identification of qualified suppliers for the product or its design.

STEP uses three basic AIM entities to define a part in AP 203. These are the *product* entity, which establishes the identification of a part (or part number), name of a part (or nomenclature), and description. The *product_definition_formation_with_ specified_source*, this entity identifies its version (or change level) and the *product_definition* or *product_definition_with_associated_documents*, which identifies the engineering discipline view that all the data related to it represents. The figure 4.4 depicts graphically the relationships among these entities that define a part using AP 203. This approach permits the representation of data at a high level of abstraction and the sharing of this data throughout all industry (PDES 1998).

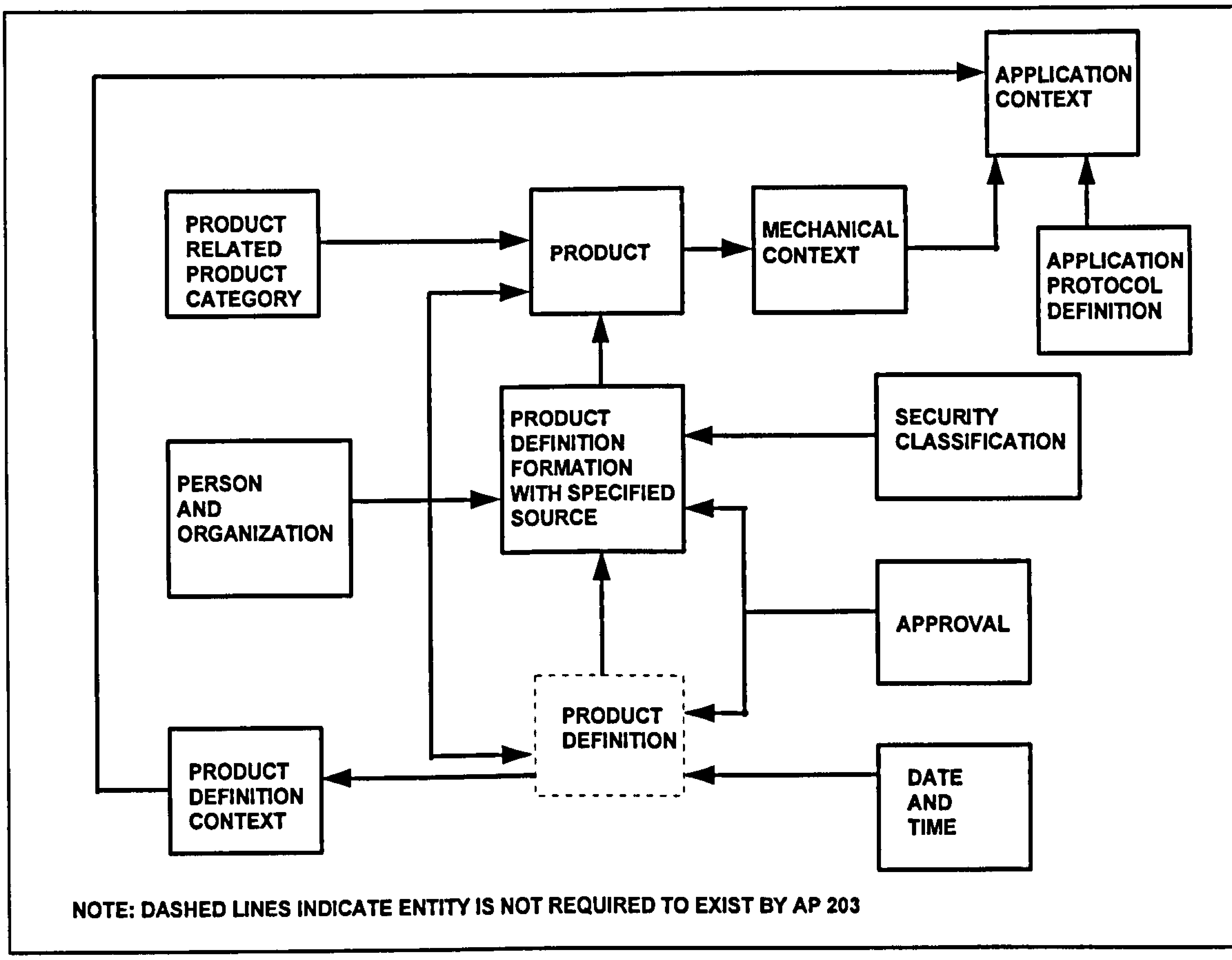


Figure 4.4 – The relationships among the entities needed to define a part in AP 203 at a high level. (PDES 1998).

4.6.2 Part 224 - Application Protocol: Mechanical Product Definition for Process Planning Using Machining Features

AP 224 is the part of STEP that specifies the representation of information needed to define a single piece mechanical part for process planning purposes (ISO10303-224 2000). The AP 224 was planned to support design and manufacturing and minimise rework, it ensures the right product is made first time (ISG 2000a). This is possible because AP 224 identifies specific characteristics of part shapes used in manufacturing. These are represented by machining features or solid models in boundary representation that may be shared by other AP's and used as an application interpreted construct (AIC) in AP 224 (ISO10303-224 2000).

AP 224 provides the geometry of the part and also the part's features, dimensions and tolerances, material requirements, and notational information. In other words, everything a manufacturer needs to know to efficiently produce the right part the first time(SCRA 2004).

The AP 224 scope is (SCRA 2000):

- Single mechanical part manufactured by machining processes,
- Parts manufactured by either milling or turning processes,
- Shapes necessary for manufacturing are defined by features,
- 3D explicit shape representation,
- Implicit feature definitions through use of parameters,
- Machining feature constructs,
- Additional part information,
- Orders,
- Customer order, work order,
- Approvals and authorisations to manufacture a part,
- Requisitions of raw stock for documenting manufacturing history; and
- Design exception notice.

A set of information requirements (IR) are defined in section 4 of AP 224, and most of this section defines details of manufacturing features. The Information Activities Model (AAM) aids to understand this scope and the IR of the protocol using a modified IDEF0 notation as in the figure 4.5 that depicts a mechanical product definition using machining features (ISO10303-224). The 2nd edition of the standard was released in May 2001 with interesting improvements such as new feature types, manufacturing assemblies and harmonization with AP 214(ISG 2000b).

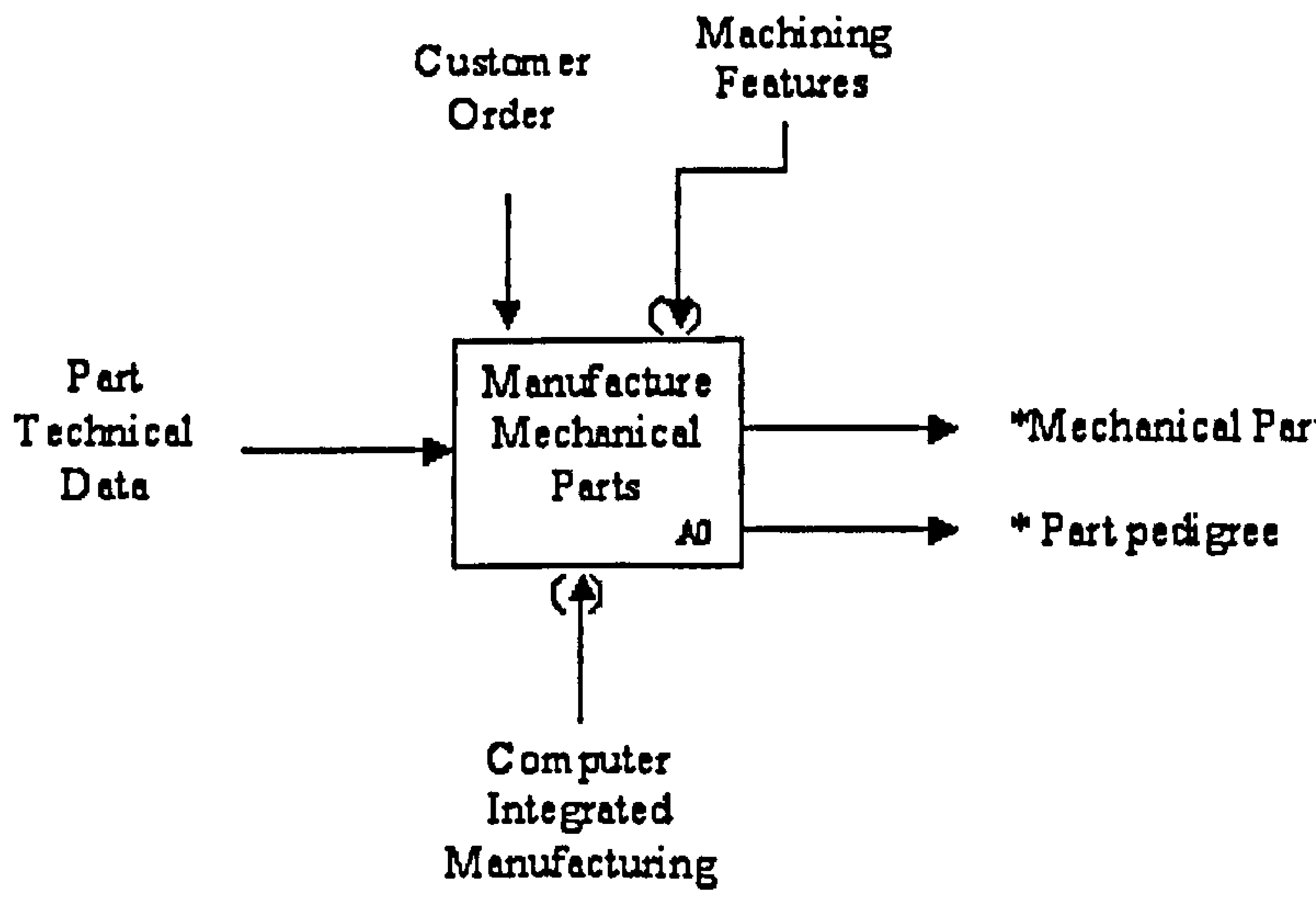


Figure 4.5 – IDEF0 A0 for mechanical products definition for process planning using features. The * indicates Input, Output, Control, Mechanism (ICOM) and activities out of scope (ISO10303-224 2000)

4.6.3 Part 240 - Application protocol: Process Plans for machined Products

During the period of this research work AP 240 replaced AP 213, the standard initially written to be used in process planning for Numerical Controlled machines. AP 240 is however, broader in scope as it is also suitable to use in manual operations. According to the current version of the evolving AP 240 standard the following represents its scope (ISO10303-240 2003):

- information out of the planning activity that is contained in the process plans for machined parts which includes: numerical controlled machines and manual operations.
- the manufacture of a single piece mechanical part, and assemblies of single piece parts for manufacturing purpose which includes: process data for part routing which includes manufacturing process and set-up sequencing and process data for operations.

- interface for capturing technical data out of the upstream application protocols which includes: product definition data, including tracking a design exception notice of a part and the initial material definition data.
- technical data for and/or out of the process planning for machined parts which includes: machining features for defining shapes necessary for manufacturing, machining feature classification structure, geometric and dimensional tolerances of the parts being manufactured, materials and properties of the parts being manufactured.
- references to standards and specifications declared in the process plan;
- work instructions for the tasks required to manufacture a part, using which include: references to the resources required to perform the work, the sequences of the work instructions and the relationships of the work to the part geometry.
- information required to support NC programming of processes specified in the process plan.
- information required to support in-process inspection specified in the process plan.
- shop floor information specified in the process plan.
- information for production planning specified in the process plan.

Thus, AP 240 covers a wide range of needs in terms of representation of information related to the process planning activity. According to AP 240 (ISO10303-240 2003), a process plan is a set of instructions which are used by programmers to create NC programs to drive the tool motion to remove material.

AP 240 specifies the data contained within a process plan but not the data necessary to perform process planning. Included in AP 240 are the relationships that exist between the different process plan data items and the relationships between these data items and the product definition data. The product definition data includes data items from the design process such as geometry, surface finish and machining tolerance(ISO10303-240 2003).

In this research work, the author has identified that some parts of the AP240 structure can be utilised to represent the data that is necessary to perform the process planning. Thus, parts such as the *manufacturing_machine_tool_resources* and its application objects have been used to represent manufacturing resources (this will be explained in chapter 7). The use of standard entities defined within the STEP standard should improve the interoperability of the manufacturing model.

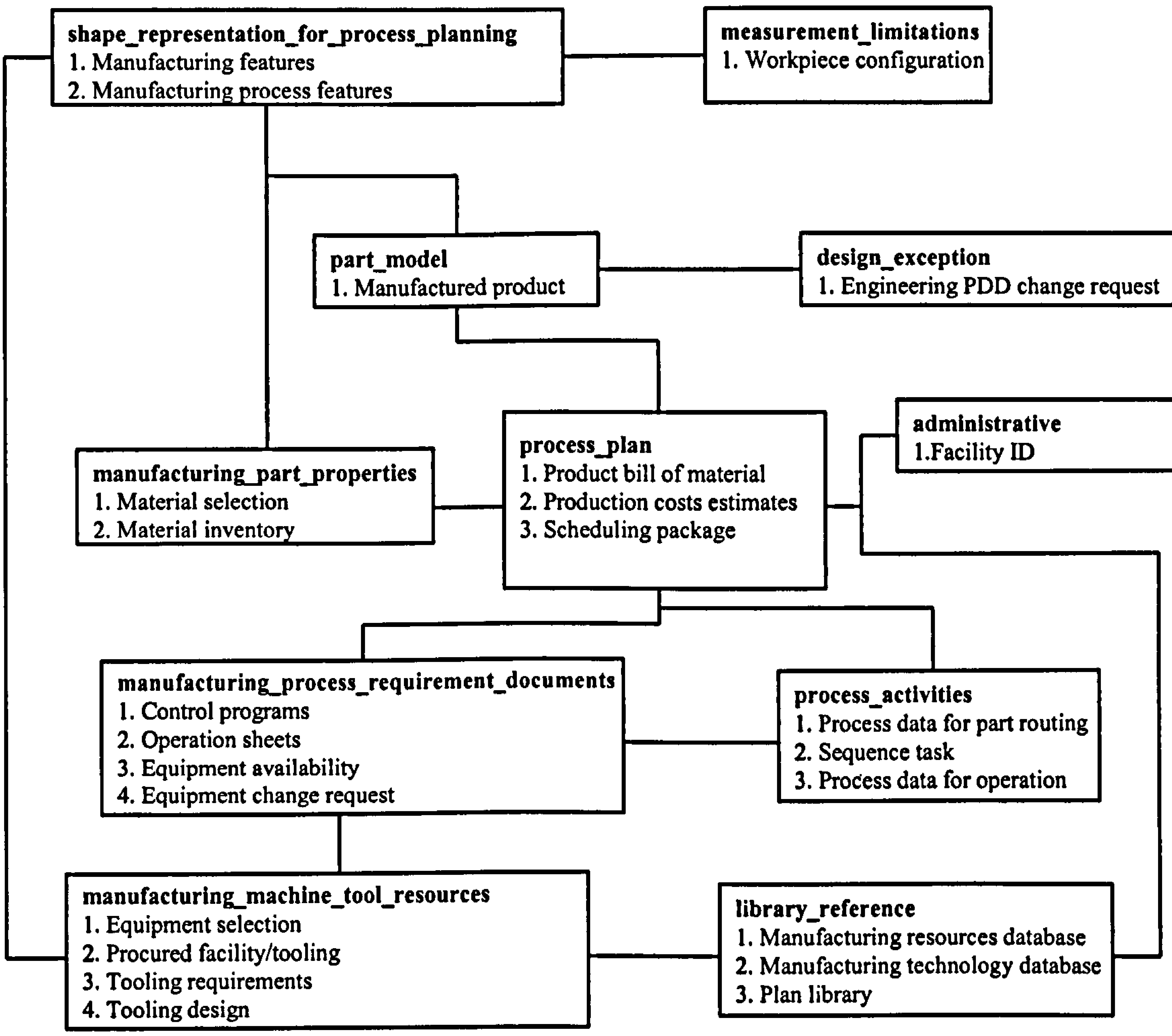


Figure 4.6 – Process Planning Data Planning Model (ISO10303-240 2003)

4.6.4 AP 219 – Dimensional Inspection Planning

This protocol manages the dimensional inspection of solid parts or assemblies and was the Proposed Work Item (PWI) submitted in June/1998 to the ISO/TC184 committee. During the writing of this thesis the AP 219 was still under development as a Committee Draft(CD). The AP specifies information requirements to manage dimensional inspection of solid parts or assemblies, which includes: administering, planning, and executing dimensional inspection as well as analysing and archiving the results. In its scope the dimensional inspection can occur at any stage of the life cycle of a product where checking for conformance with a design specification is required (ISG 2000b). It is out of the scope of AP219 (ISO/CD10303-219 2002):

- Developing or modifying manufacturing process information,
- Generating geometry (creating the CAD model),
- Generating tolerance requirements, and
- Inspection of material properties.

An important amount of entities used within this AP are based on AP 224 entities. Most of the manufacturing features and tolerance definitions are actually references to AP 224 entities. This means that a high level of integration has been achieved so far in the development of this standard.

It is important to note two of the units of functionality, namely: *Dimensional_ measurement_features* , in which *Dm_Feature* is the base class for the features related to measurement, and the unit of functionality *measurement_limitations* which contains the information needed to identify important dimensions and relationships between them and the part's shape. In *measurement_limitation* are included the tolerances and many types of datum.

4.6.5 AP 238 - Application Interpreted Model for Computerized Numerical Controllers

This AP is the Application Interpreted Model (AIM) of the ISO 14649 Standard, which is the Application Reference Model (ARM) (see sections 4.4.8 and 4.4.9). AP 238 specifies the integrated resources used to describe the information requirements identified by ISO 14649(ISO 10303-238 2004). It is claimed that it is "in manner consistent with the part shape, feature, and geometric tolerance information created by design and process planning activities and represented by APs 203, 214, 224 and 240" (ISO 10303-238 2004). Feeney at al. (2003) say that the primary difference between ISO 14649 and ISO 10303-238 is the degree to which they use the STEP representation methods and technical architecture. They also explain that the standard uses the EXPRESS models in ISO14649 "with a few modifications" (Feeney at al. 2003) then maps it into the STEP integrated resources.

The scope of AP 238 is described as being (ISO 10303-238 2004):

- mechanical parts for manufacturing
- manufacturing process descriptions, including manufacturing operations, sequences of operations, and associated information as defined in ISO 14649
- the AS-IS and TO-BE shapes of a mechanical part
- manufacturing features of a part
- manufacturing tolerance requirements of a part
- tool requirements for machining operations
- tool paths for machining operations
- manufacture of mechanical products using manufacturing processes defined in ISO 14649
- manufacturing product discipline view

AIM is used to provide a way to share application information through databases that implement ISO 10303 generic resources without needing to modify the structure of the database (ISO 14649-1 2002).

From the analysis of the files generated by ISO10303-238 and from ISO14649 it can be said that the AP 238 is a more verbose way to describe the same NC program. Therefore, AP238 should fit better together other parts of STEP. A discussion over the advantages and disadvantages of the two standards can be found in Feeney at al. (2003) and Wolf (2003).

During most of the development of the research described in this thesis AP 238 had only the milling model and the DIS version with the turning capabilities becoming available during the writing up of this thesis. Thus, the ARM (ISO 14649) was used to develop the models described in Chapter 7.

4.7 Review Summary

Since the early CAD and CAM systems were developed the search for efficient data exchange has been a priority. With the wide range of vendor specific bespoke translators the research community has put enormous efforts into STEP standards to provide an encompassing solution.

Though these efforts have enabled vendors to generate STEP translators, their use has only given limited success. A major stumbling block has been the links from CAD to CNC, due to limited programming capabilities and the closed nature of CNC controllers. This has meant that STEP has only been used as a CAD to CAM translator with little or no data transfer for process planning or manufacturing knowledge. Over the last 6 years, but more specifically from 2002 significant efforts have been made in the STEP community to close the design to manufacturing divide, which the author believes will empower the existing STEP standards. These new developments termed STEP Compliant Manufacturing are outlined in Chapter 5.

Chapter 5

Review on STEP Compliant Manufacturing

5.1 Introduction

This chapter reviews the developments in standards for NC manufacture. The initial part outlines the beginning of the introduction of NC standards including ISO 6983. The major part of this chapter reviews the new ISO 14649 standard for NC manufacture, outlining its structure for milling and turning.

5.2 Background

In the last 50 years the industrial world has seen a revolution comparable with the first industrial revolution. This was the adoption of computers in the whole life cycle of products since the conception/design, throughout planning, manufacture, and inspection. An important role was, and still is, performed by machine tools that are controlled by electronic devices. In this group the machines that use Computer Numerical Control (CNC) play a remarkable role and bring the need of support systems. In Section 3.4 the development of software and hardware to support NC manufacture was described. Although these developments have improved the software tools and the architecture of CNC machine tools, vendors and users are still seeking a common language for CAD, CAPP, CAM, and CNC, which integrates and translates the knowledge of each stage.

It is with this aim that STEP compliant NC programming is being developed to provide consistent standards for automatic and quality oriented CNC component manufacture. To this end over the last 6 years, significant efforts have been directed in the development of a new ISO standard based on STEP to bridge the information divide between product design and CNC manufacture. To solve these problems a new data interface entitled ISO 14649 (known as STEP-NC) (ISO14649-1 2002, Weck et al. 2001) has been developed under the ISO Technical Committee TC184 in the Sub-Committee SC1 Workgroup WG7 based on ISO 10303. The introduction of this standard aims to integrate STEP compliant information across the whole product cycle of CAD, CAPP, CAM and CNC (Computer Aided Design, Process Planning, Manufacturing and Computer Numerical Control).

The standard ISO14649 has been initially developed through an international R & D programme entitled STEP-NC. This programme has been recognised as an IMS (Intelligent Manufacturing Systems) programme co-ordinated across 4 worldwide regions each with individual projects namely Europe, Korea, Switzerland and the USA (Weck 2001). STEP-NC Europe was responsible for milling, turning and inspection of the ISO14649 standard, it has 15 partners, led by Siemens and is undertaking developments on the ARM version of ISO 14649 with the support of research institutes such WZL, Aachen University and ISW Stuttgart University. The Swiss are led by EPFL (Ecole Polythecnique Federale de Lausanne) are undertaking the developments of the standard for wire-cut and die-sink EDM. The work in Korea has been developed at the National Research Laboratory (NRL) for STEP-NC in collaboration with Pohang University. ERC-ACI - Seoul National University are providing further developments in milling and turning architectures for ISO14649 compliant controllers. Finally the STEP-NC programme in the USA termed Super Model led by STEP Tools Inc. is making major advances with the AIM version of the ISO 14649 standard to fully automate the CAD to CNC manufacturing process through the use of AP 238(See AP 238 in Section 4.6.5). Super Model involves a group of industrial partners that includes Boeing, Lockhead Martin, General Electric and General Motors, together with CAM vendors such as Gibbs Associates and MasterCAM (Newman 2004).

Contrary to the NC programming standard ISO 6983, known by the G and M codes, the ISO 14649 is not a method for programming and although it is possible, it does not need to describe the tool movements for a CNC machine. Instead, ISO 14649 provides an object oriented data model for CNC's with a detailed and structured data interface that incorporates feature based programming where there is a range of information such as geometric information using features similar to AP224 definitions, type of tools and their data, the operations to perform, and the work plan (Weck et al. 2001). This means that as Suh and colleagues (Suh et al. 2002) point out the ISO 14649 specifies the information contents and semantics to various CNC processes.

In the following sections the standards for NC manufacturing are depicted with special attention to the new ISO 14649 (STEP-NC) Standard and AP 238.

5.3 The Standard ISO 6983

The use of a standard language to program machine tools has been a major area of research and development since the beginning of the use of software programming. The ISO and national standards bodies have consciously developed standards such as DIN 66025 (Weyrich et al. 2000) and ISO 6983 (Numerical control of machines – Program format of address words) (ISO6983-1 1982) were developed and are the basis of NC programming that is well known today. The ISO 6983 is divided into 3 parts where Part 1 is an International Standard (IS) since 1982, however Parts 2 and 3 never progressed beyond the DIS (Draft International Standard) phase even though they were developed in 1988 (ISO6983-2 1988, ISO6983-3 1988). The contents of ISO 6983 parts are described below.

(i) Part 1 specifies the requirements and makes recommendations for data format for positioning, motion and contouring systems for NC machines, (ISO6893-1 1982)
(ii) Part 2 specifies coding and maintenance of preparatory (G) and miscellaneous (M) functions, and
(iii) Part 3 specifies coding of miscellaneous functions classes 1 to 9.

The main feature of this standard is that NC programming of components is basically formed using G codes which provide motion commands such as linear and circular interpolation (Weyrich et al. 2000), and switching instructions using M codes (Step-NC 2000a). This means that the operations are described as a sequence of tool motions along the axes (e.g. X, Y, Z, A, B, C) and calls of some specific switching functions for a given machine tool, such as rotate the table of a milling machine by a certain amount of degrees, or switch the coolant on/off. The codes are address words for controllers. A typical example line of an ISO 6983 program line is showed in figure 5.1.

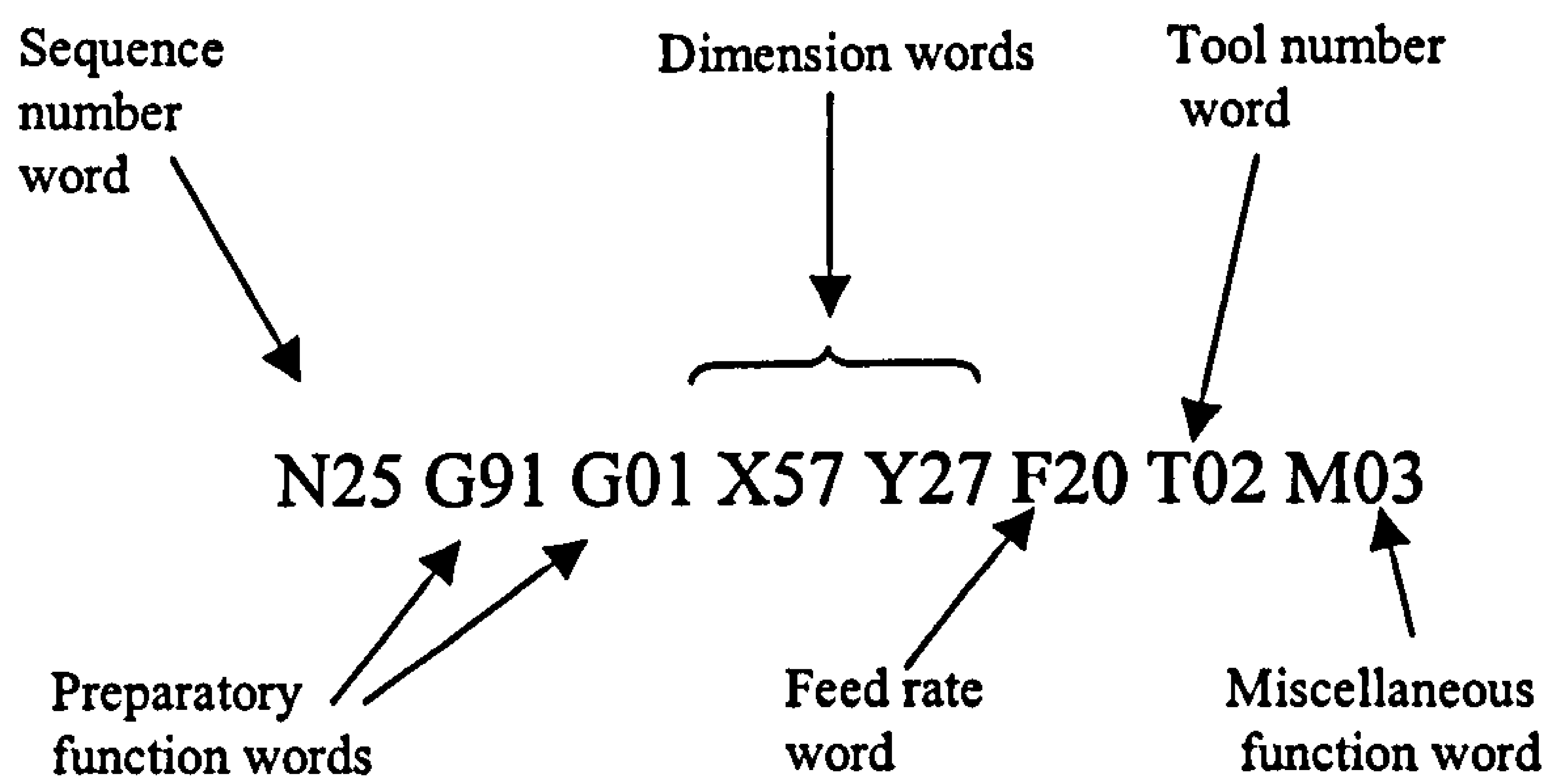


Figure 5.1 – Program line in ISO 6983 code.(Adapted from Williams 1988)

One of the remarkable characteristics of these programs is the size. Only for very simple parts the size is small enough for manual use, and in general and mainly for complex parts such as tool moulds, the program may have many Mbytes. That makes the last minute changes at the machine's controller very difficult. Another problem is the poor standardisation between controllers' vendors. It is normally impossible to use a program designed for one machine on a different NC machine (Step-NC 2000c) without modification. In general the user needs to post-process the program and prove out the program again on another machine. This implies greater costs through the increase of set-up time and operation planning.

In order to simplify the programming activity and make NC programs more compact, the ISO 6983 standard enables a special set of G codes called fixed or canned cycles, that have pre-programmed functions for example: a cycle to deep drill with chip break (G83) where the tool moves inside and out the hole to relieve and/or break the metal chips. Thus depends on the depth of the hole where it may replace many standard lines of coding, a simple use of a such canned cycle with some parameters such as hole depth and cutting depth increments are enough to describe the operation

The more common and standardised canned cycles are drilling cycles, which normally use the words G81 to G89 and the G80 for cancelling the cycle. Other canned cycles, which are usually vendor specific, could be pocket machining cycles, and the use of probing cycles. ISO 6983 compliant controllers can also provide sub-program and macro facilities.

The subprograms are patterns of lines that are used several times in a program or in more than one program. They are stored in another part of the controller's memory and used when needed. The implementation of subprograms is vendor specific and may have differences between two controllers.

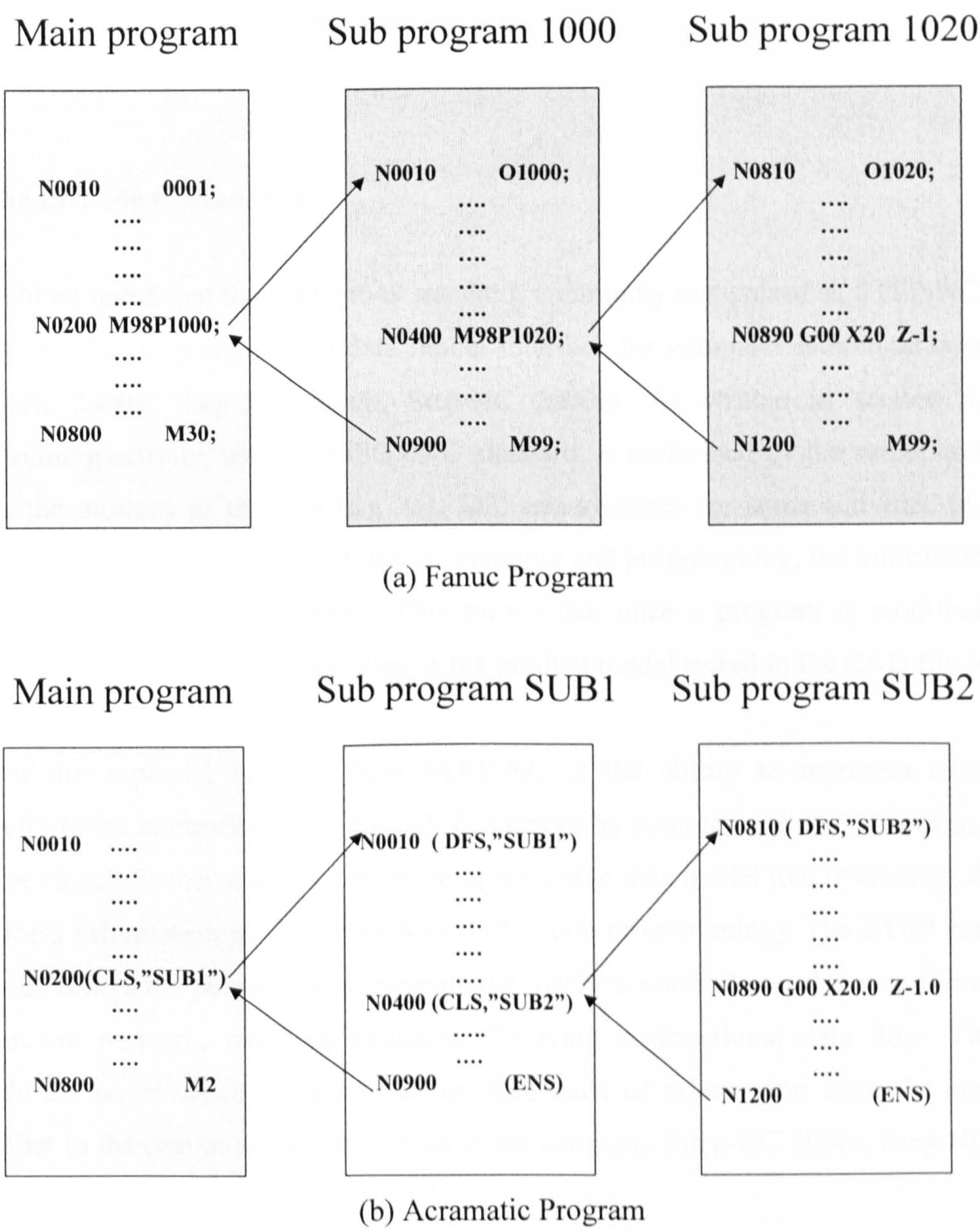


Figure 5.2 Subprogram's call in a main program
(Adapted From Fanuc(1988) and Cincinnati (1997)).

Macros are groups of functions that are in fact sub-programs. They are stored in the controller's memory in the same way as sub-programs and are called as required. Macros may be supplied by the machine tool builder and can also be modified by the end user.

These canned cycles and sub-programs variations in coding illustrates some of the problems in program interoperability in CNC machine tools. The need for a standardised approach allowing interoperable CNC manufacturing is long overdue. It is with this aim that STEP manufacturing standards are evolving.

5.4 The ISO 14649 Standard

It should be noted that the ISO 14649 standard, commonly recognised as STEP-NC, is not a programming language, but a data model interface for computer numerical controllers (Step-NC 2000a, Step-NC 2000b, Step-NC 2000c). As written in section 5.3, the programming activity, using the ISO 6983 standard, is performed by the use of codes that enable the motions of the tool (e.g. G1, G2) and switches for some activities (e.g. M3, M8). Thus in the process chain of design, planning and programming, the information flow is unidirectional (Step-NC 2000c). This means that once a program is modified, it no longer corresponds to the process plan or the product model stored in the CAD file format.

One of the expected benefits from STEP-NC is the ability to represent component geometry in the controller either through features or by complex regions. However, STEP-NC goes much further and has a more comprehensive data model that overcomes the lack of process information in ISO 6983 files (G/M code programming). The STEP compliant approach brings the possibility to integrate the machine controller to the overall enterprise information network, with the intention of having bi-directional data flow. This will provide the novel capability for upstream feed back of information from the numerical controller to the design and process areas in the company (Step-NC 2000c, Step-NC 2003, Rosso-Jr et al. 2002, Newman et al 2003).

Figure 5.3 depicts the differences between the current state of art in NC manufacture using ISO 6983 where data flow is unidirectional from the CAD/CAM system to the CNC and bi-directional when using STEP-NC. Although this approach has been partially adopted commercially by some CAM/CNC systems such as the CAMWARE/Mazatrol system (Yamazaki 2003), these systems use their own proprietary data format which does not allow integration into a company's product and manufacturing data models. In addition, when using ISO 6983 the information available in the CAD/CAM system is partially lost when post-processed into G/M codes, as the standard does not provide support for most of the information (Weck et al. 2001, Proctor et al. 2002).

In comparison, the ISO 14649 standard provides a feature based object oriented data model for the next generation of intelligent CNC's (ISO14649-1 2002). It is systematically detailed with a structured data interface that incorporates the component geometry through feature-based programming. In addition Figure 5.4 illustrates the major differences in use between the ISO 6983 and ISO14649.

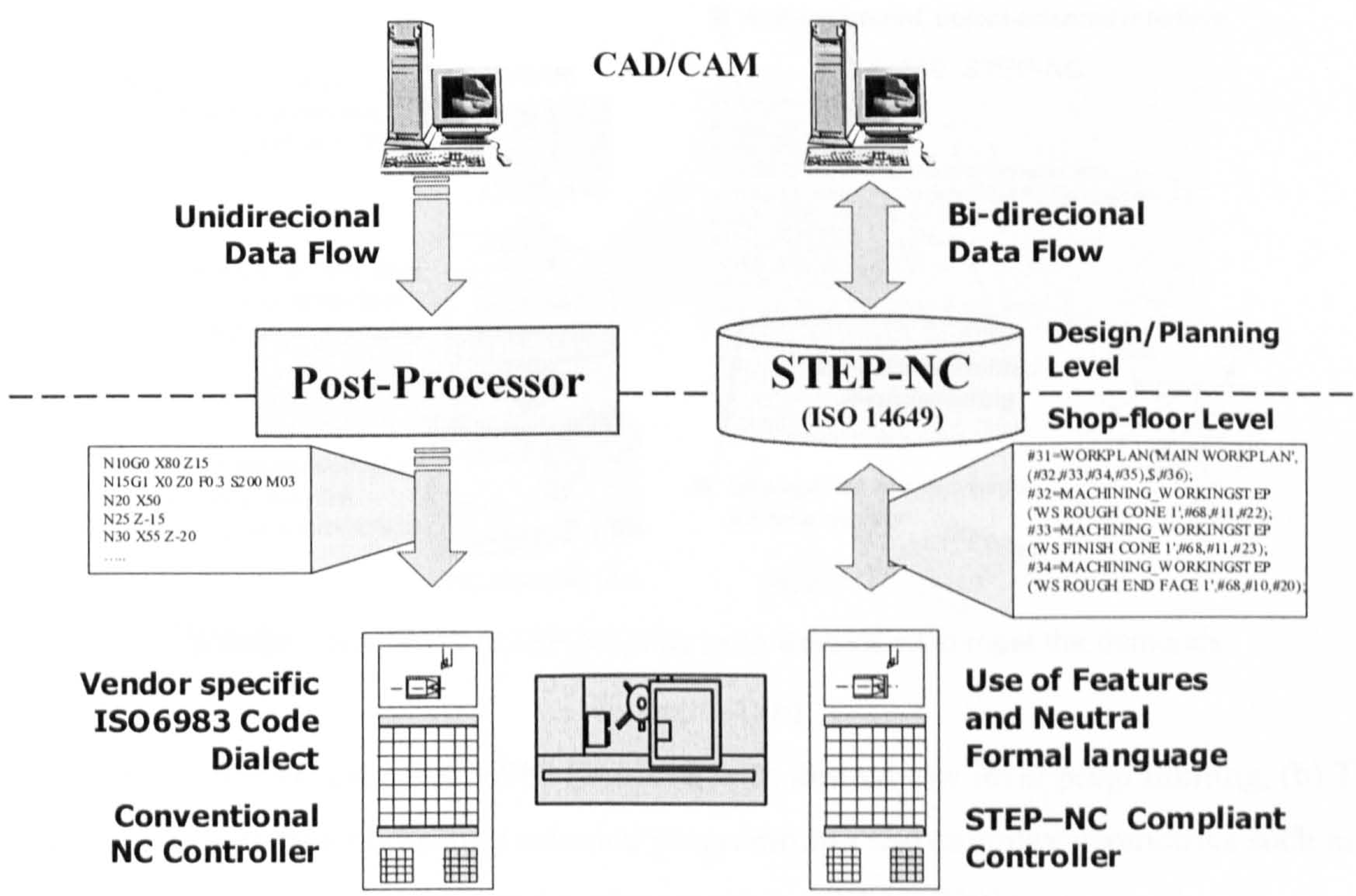


Figure 5.3 - Differences between the data flow using of ISO 6983 in NC programming and with the use of ISO 14649.

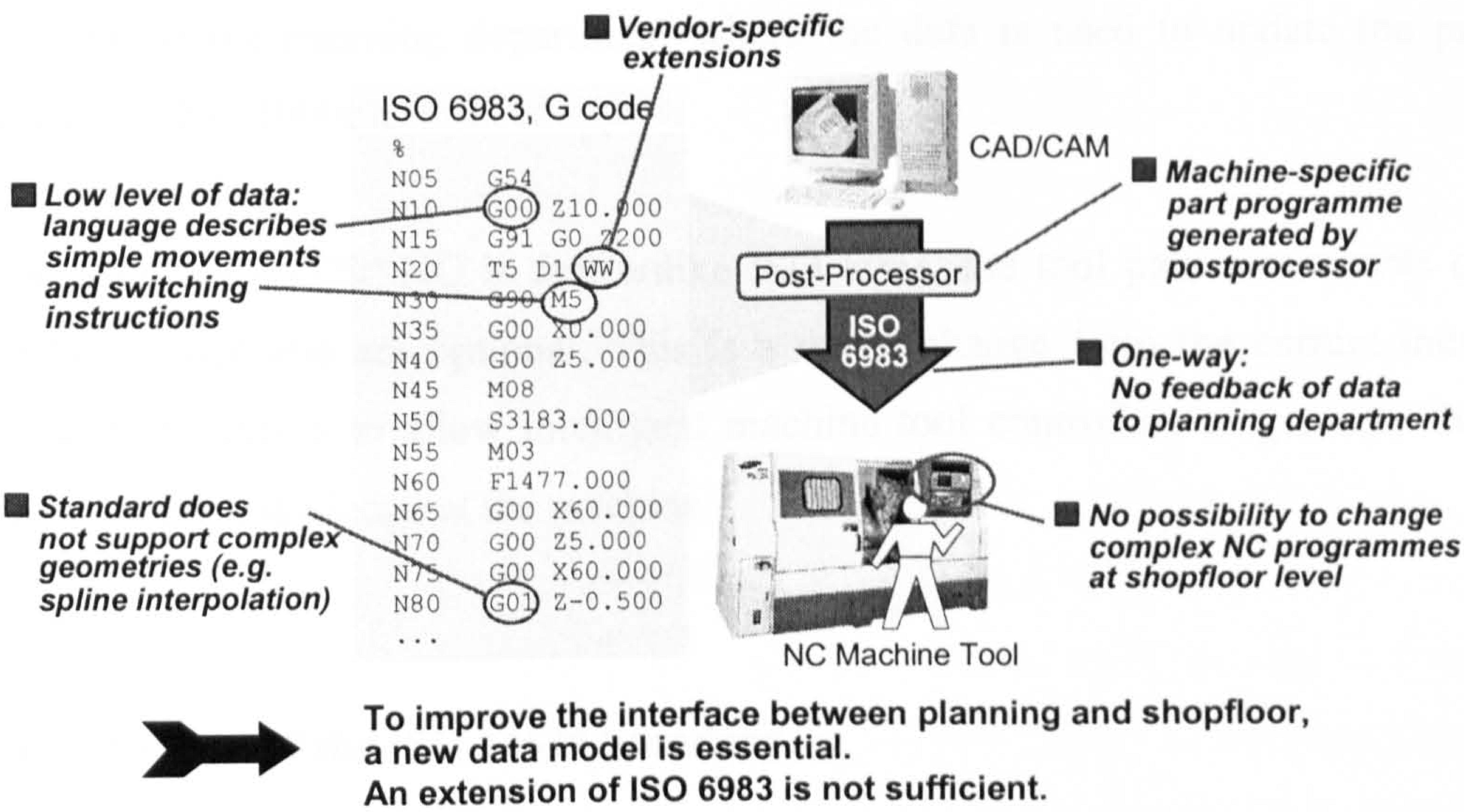


Figure 5.4(a)

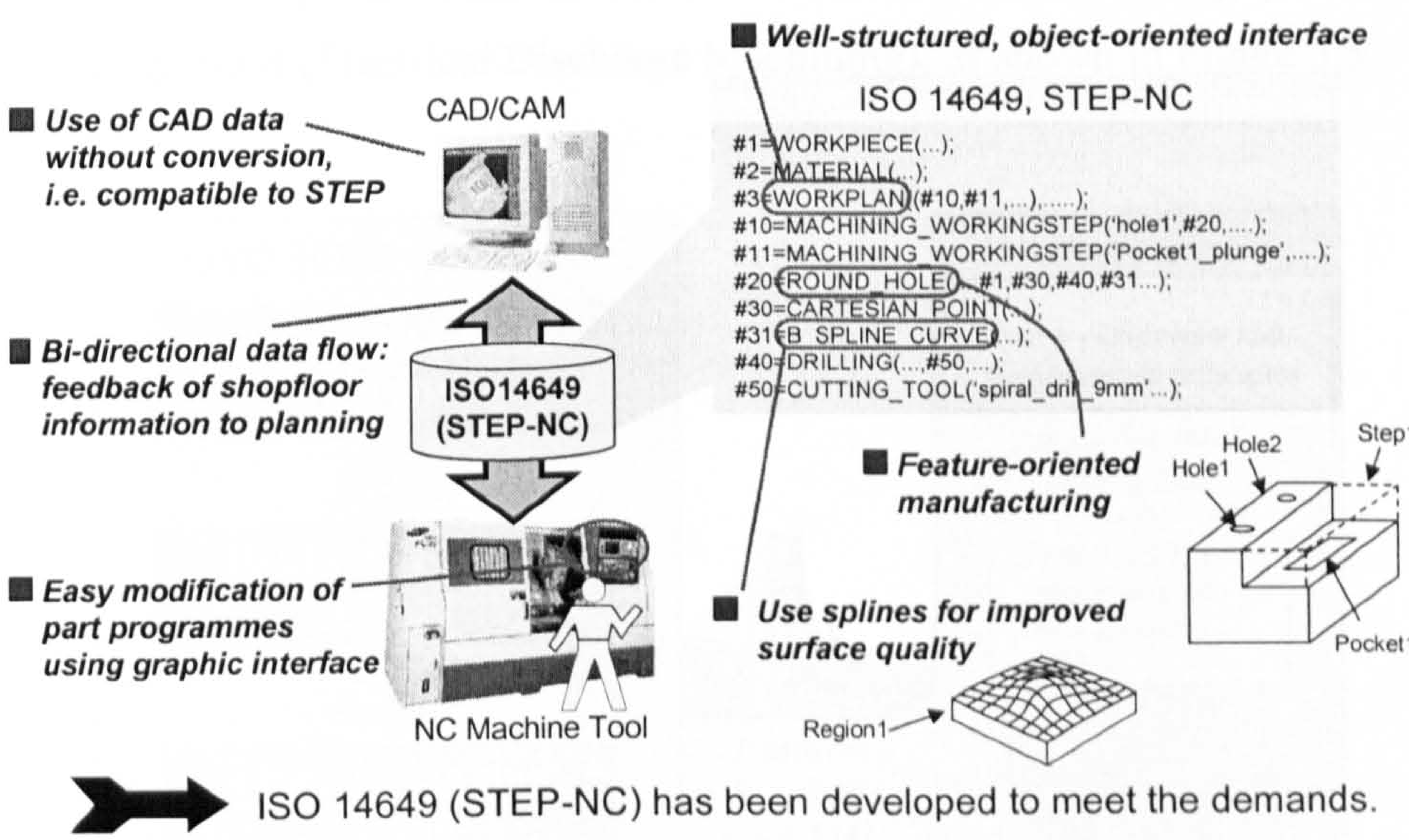


Figure 5.4 (b)

Figure 5.4 – (a) The use of ISO6983 Standard with limited low level programming, (b) The use of ISO 14649 with Feature oriented programming and complex geometries such as splines and surfaces regions. (Weck 2001)

Actually the keystone of ISO 14649 is the use of an approach that is near object-oriented. It uses a data model that has an object-oriented view in terms of STEP (AP224) manufacturing features instead of the programming of the tool paths and tool functions (ISO14649-1 2002). Apart from this remarkable capability the ISO 14649 also allows a two-way manufacturing chain. This means that when a program is modified, the user may send it back to the planning department where the data is used to update the process planning (Step-NC 2000b).

A major issue with STEP-NC is that unlike ISO 6983, the tool path movements do not have to be defined and are optional. This is a major change from the current industrial practice and the aim is to allow intelligent machine tool controllers to generate the tool path based on the knowledge at the machine.

5.5 The Structure of the ISO 14649 Standard.

The standard follows the typical STEP structure where there is a general standard for guidelines and many parts which describe each branch of technology/process such as milling, turning, EDM (Electrical Discharge Machining), as shown in Figure 5.5.

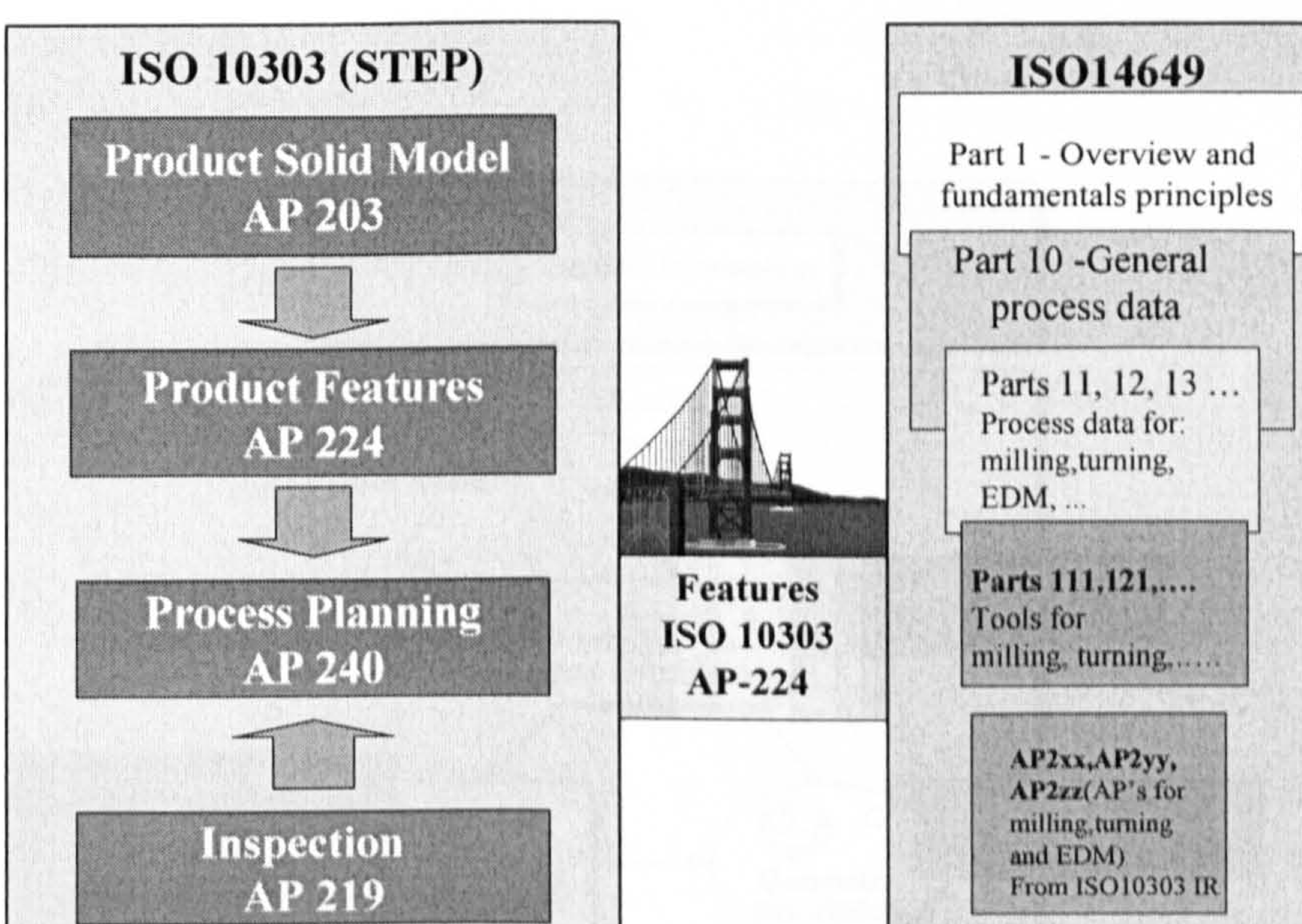


Figure 5.5 – The relationship between ISO 10303 and ISO 14649.

Figure 5.5 also depicts the relationship between STEP AP's and ISO 14649 and the actual structure of ISO 14649. In fact, the bridge to transform a product model in a machining program is the features technology. Once modelled the product information may be stored in a file that is compliant with AP 203. Their features are extracted in AP 224 format and then the process is planned using AP 240. Now, a CAM system needs to be used and generates a STEP compliant NC program. If inspection is needed, AP 219 also should be used in the process (Step-NC 2000b, ISO14649-1 2002). The following sections describe the published parts of ISO 14649 together with their advantages and disadvantages.

5.5.1 ISO 14649 Part 1 – An Overview and Fundamental Principles

ISO 14649 Part 1 (ISO14649-1 2002) defines the basis of the standard, describing the relationship between ISO 14649 and ISO 10303 namely the AP's 203, 213[1], 224, and 219. It outlines the general file structure of a physical file in two sections one entitled "HEADER" where general information about the part program is stored and a "DATA" section in which all information about manufacturing tasks and geometry to produce a part is held. The second section contains three important parts namely the *Workplan & Executables*, *Technology Description*, and *Geometric Description*. It also defines basically that this standard is a different NC programming approach with an Object-oriented Data Model. Figure 5.6 depicts the structure of the object-oriented data model for ISO 14649.

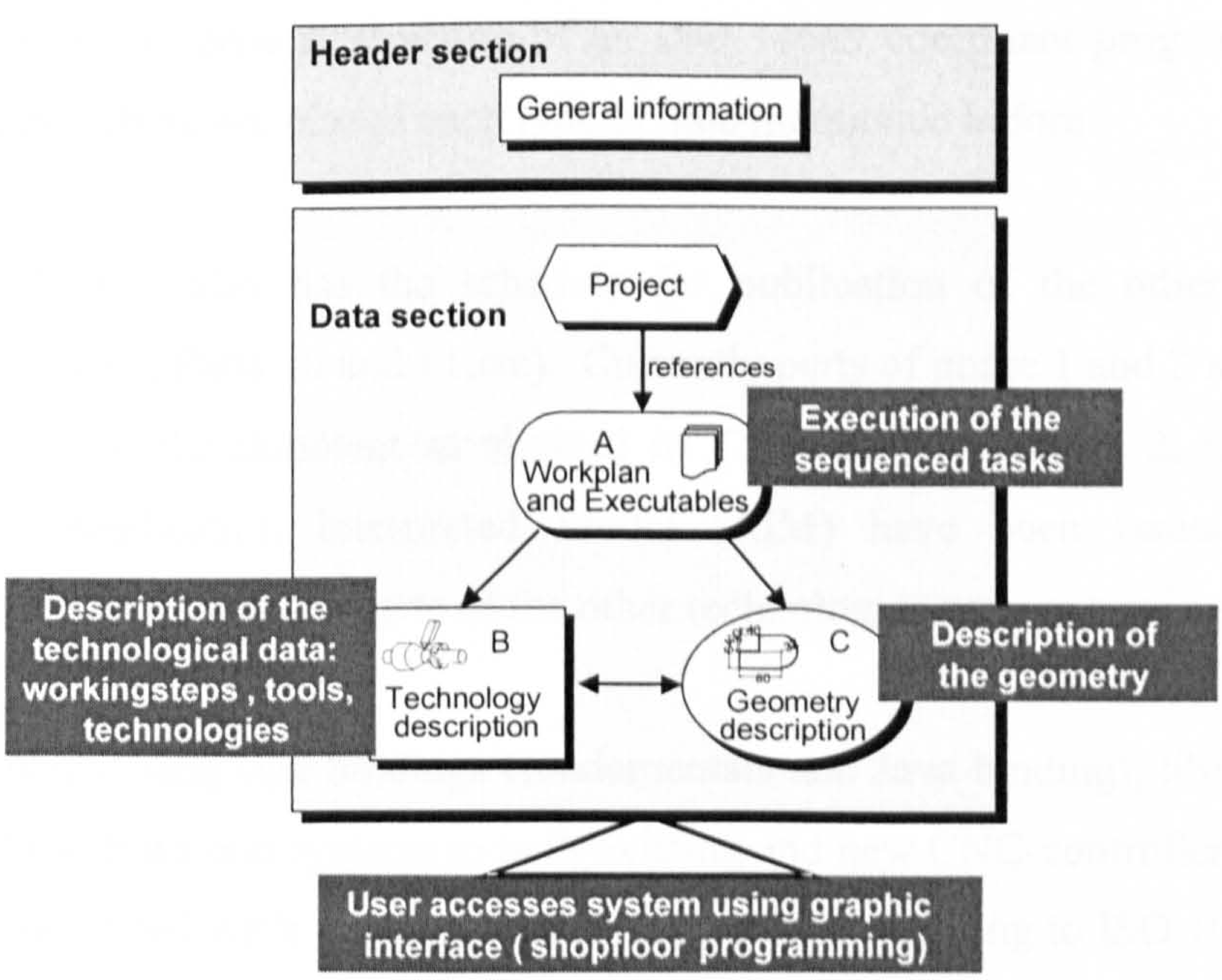


Figure 5.6 – The structure of ISO 14649 Object-oriented Data Model (From Step-NC 2000b).

[1] The AP 213 has been replaced by AP 240 but it is the reference in the standard

The *workplan* and *executables* are part of the core idea of how to execute the tasks. There are 3 types of executables namely: *workingsteps, NC_functions* and the *program structure.* The *workingsteps* are generally a description of the operations performed in a single operation using a single tool (e.g. the operation to drill a through role). *NC_functions* are statements such as display a message, an optional stop, and others that do not need interpolation of axes. The *program structure* called *executable* is a class of entities that are used to control the program flow such as *while, if, parallel, and workplan.* The *workplan* has a special role in the control of the program flow, as it controls the sequence of the *workingsteps.* This implies that if the user changes the sequence of *workingsteps* in the *workplan,* it is possible to achieve a change in the sequence of the operations. Therefore, the remaining definitions such as geometry and technology continue unchanged. The technology description is a definition of the *workingsteps* found in the *workplan.* This includes a large amount of process data such as machine functions, tool data and so on. The geometric description of the set up and features position are obtained through the entities defined in ISO 10303 formats (as described in parts 41, 42, and 43 of ISO 10303) (ISO10303-41 1994, ISO10303-42 1994, ISO10303-43 1994). Figure 5.7 shows the author's view of the general structure of an ISO 14649 compliant program in details to ease understand where are placed each type of data mentioned before.

ISO14649-1 (2002) also has the schedule for publication of the other parts of ISO 146949(e.g. Part 12, Parts 10 and 11,etc). Currently parts of phase 1 and 2 are published in different stages of development as showed in Table 5.1. In phase 2, the Application Protocols to Application Interpreted Model (AIM) have been issued as AP 238 (ISO10303-238 2004) and the parts of the other technologies such as turning and EDM.

In the third phase, language bindings (fundamentals and Java binding), libraries to CAM-systems, and the front-end systems to both existing and new CNC-controllers (ISO14649-1 2002). The mentioned AP's together with the ISO 14649 mapping to ISO 10303 integrated resources (IR), and the ISO 10303 XML representations of EXPRESS schemas and data (ISO 10303 Part 28) are the responsibility of ISO/SC4 Committee (the same that is responsible for ISO 10303) instead of SC1 (which is responsible only for ISO 14649).

Figure 5.8 shows the distribution of responsibilities between the ISO Technical Committees (TCs) and industry as it is clear that the implementation of these standards in the new generation of NC controllers will need to be realised by the NC controllers' industry, according to the STEP standards.

Table 5.1 – Currently published parts of ISO 14649

Part	Contents	Current Stage
1	Overview and Fundamental concepts	IS
10	General Process data which gives the fundamentals for all technologies	IS
11	Process data for milling	IS
111	Tools for milling	FDIS
12	Process data for turning	FDIS
121	Tools for turning	FDIS
13	Process data for wire EDM	DIS
14	Process data for sink EDM	DIS
15	Glass cutting & Wood cutting process	CD
16	Data for touch probing based inspection	WD

IS: International Standard   Final Draft of International Standard

CD: Committee Draft   WD: Work Draft

5.6 ISO 14649 Part 10 - General Data Process

This Part of ISO 14649 is a description of the general process data for NC machining and is described in the schema called "*machining_schema*". This schema provides a definition of the data types that are generally needed for different technologies such as milling, turning, grinding, and EDM. However, it is the author's opinion that, this part of the standard is actually centred on 2 ½ D milling and suffers from a lack of generality. Therefore, most of the contents relate to 2 ½ D features.

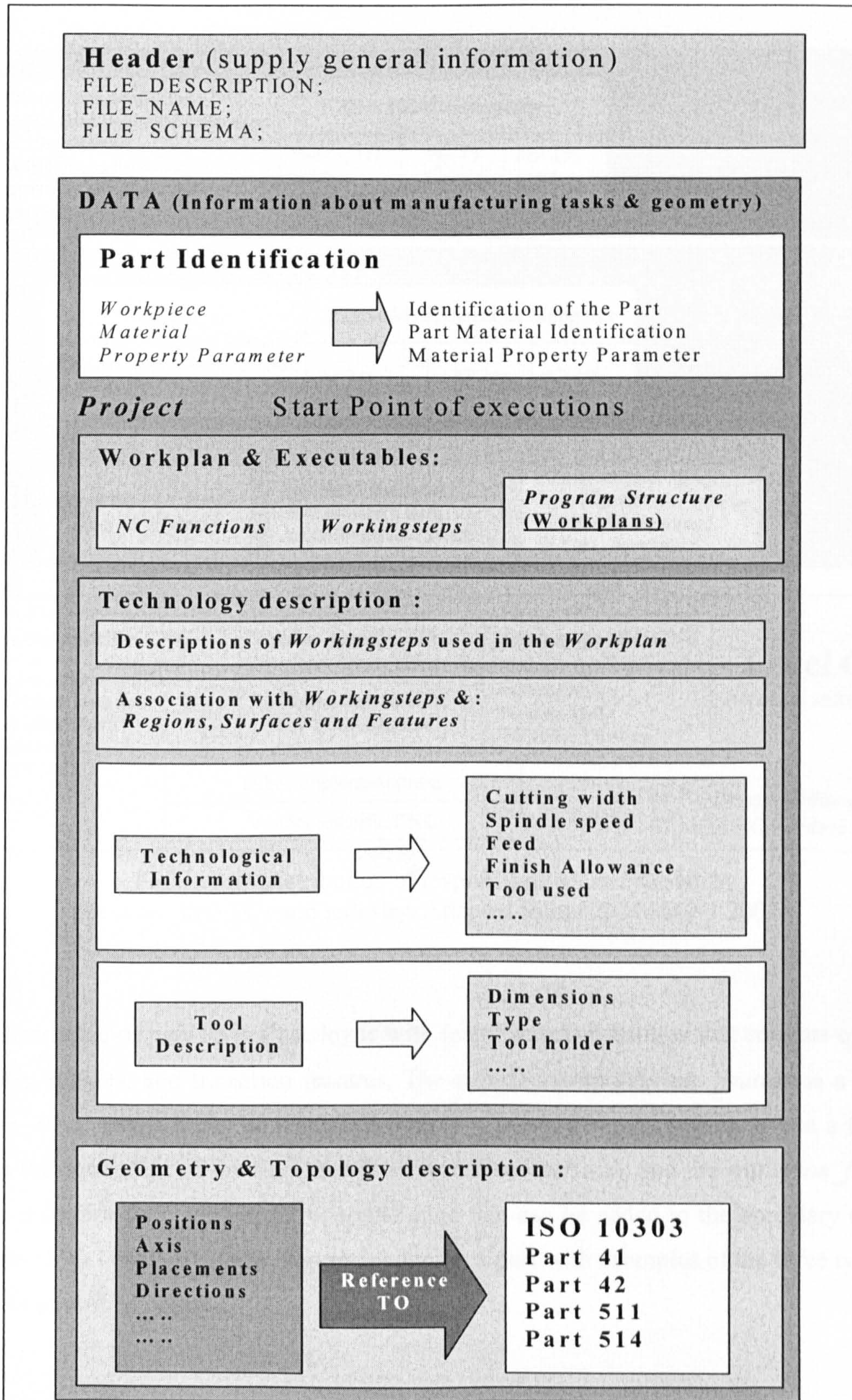


Figure 5.7 – Details of the typical structure of ISO 14649 program (Rosso-Jr, 2001)

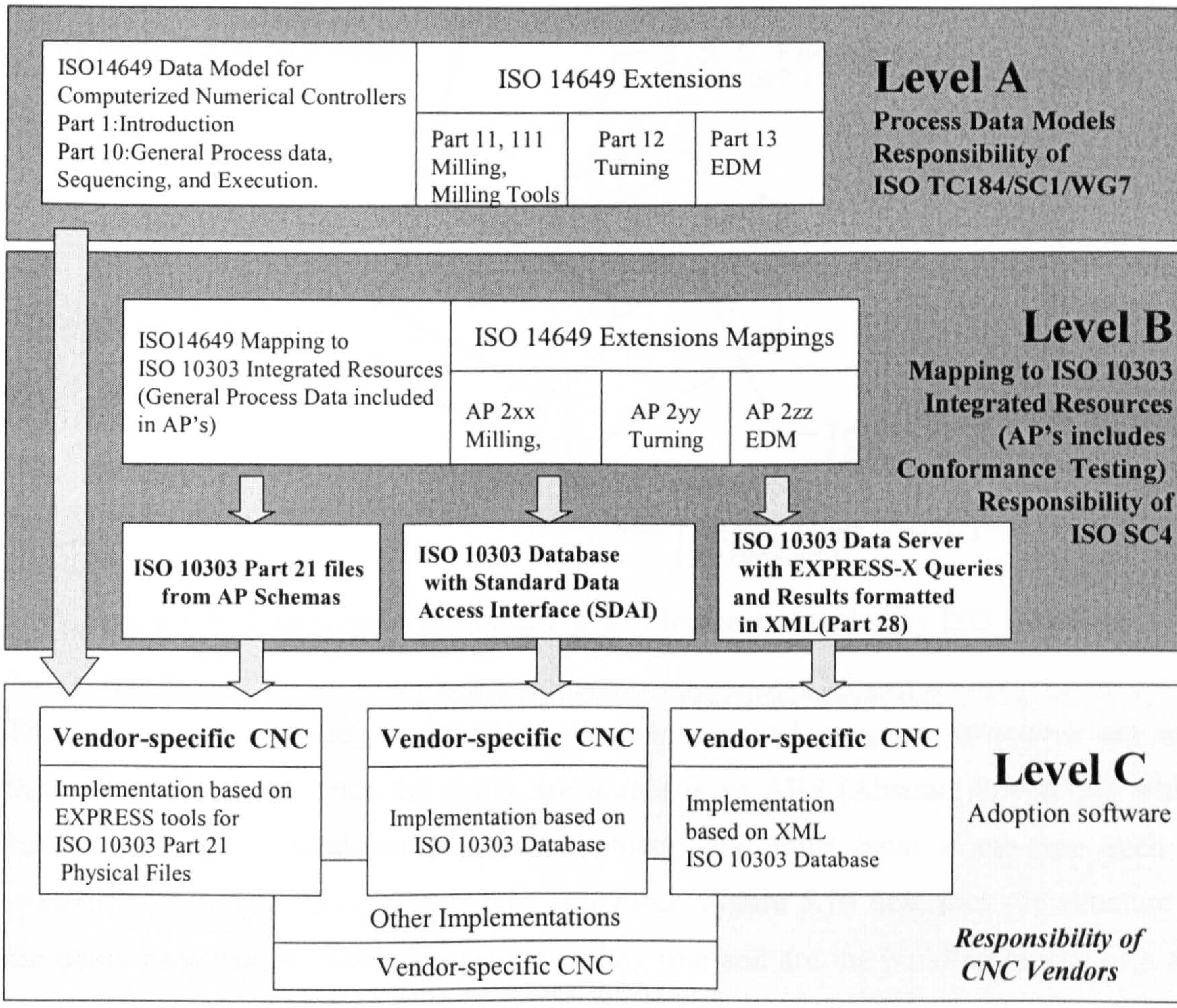


Figure 5.8- Distribution of responsibilities and activities between ISO TCs and industry. Adapted from (ISO14649-1 2002)

The foundation of part 10 is a catalogue with manufacturing features that consists of 2½D features, regions, and transition features. The *two5D_manufacturing _feature* is a 2½ D feature (that means it can be machined with 2 ½ axes), a *region* (which is like a feature that is the equivalent of the final free form workpiece surface), and the *transition_feature* that is a feature such as chamfer or round edge that can be added to the boundary of two features (ISO 14649-10 2002). Figure 5.9 depicts a part with examples of the three types of features described before.

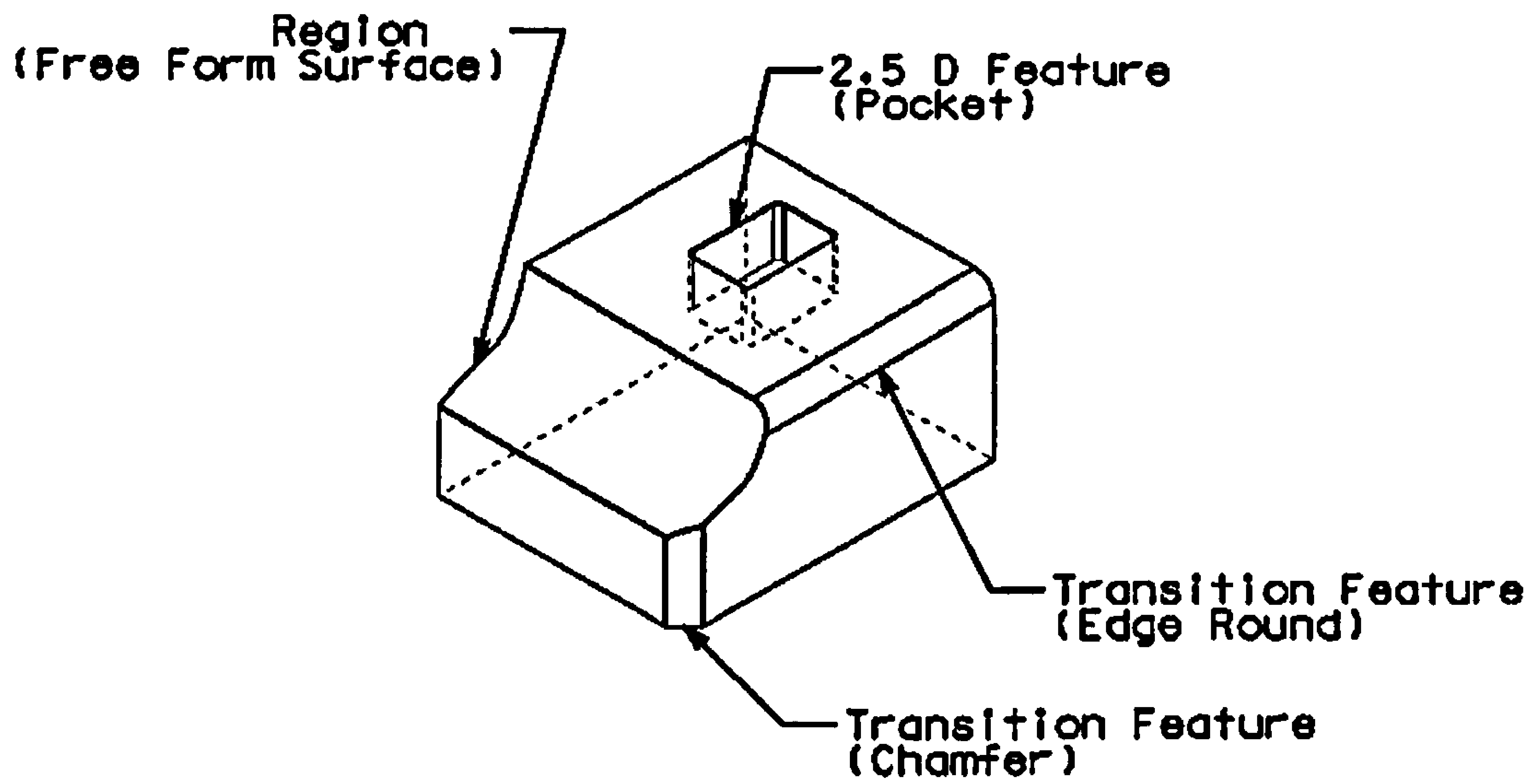


Figure 5.9 – Examples of the three types of features provided by ISO 14649-10.

The executables such as *workingsteps, nc_function*, and *program_structures* are also thoroughly described. Thus the entity *executable* is an ABS (Abstract Supertype) which means that it is a base entity (idea or object) and must have a sub-type such as *workingsteps, nc_function, or program_structures.* Figure 5.10 describes the structure of the entity executables. *Workingsteps* play a key role and are the building blocks of a NC program using the ISO 14649 Standard. They have as characteristic the possible re-usability of information from an operation for several features in a workpiece.

```
ENTITY executable
ABSTRACT SUPERTYPE OF (ONEOF(workingstep,
nc_function, program_structure));
its_id: identifier;
(*
Informal proposition:
its_id shall be unique within the part programme.
*)
END ENTITY;
```

Figure 5.10 – Structure of the entity *executable* (ISO14649-10 2002).

A *workingstep* is an ABS as well, and has as children the entities *machining_workingstep, rapid_movement, and touch_probing.* Figure 5.11 describes the entity *workingstep.*

```
ENTITY workingstep
ABSTRACT SUPERTYPE OF (ONEOF (machining_workingstep,
rapid_movement,
 touch_probing))
SUBTYPE OF (executable);
its_secplane : elementary_surface;
END_ENTITY;
```

Figure 5.11 – Definition of entity *workingstep* (ISO14649-10 2002).

A *machining_workingstep* must have a manufacturing feature as an attribute, it cannot exist independently from a feature as it represents the association between a feature and one operation. The attributes in the *machining_workingstep* are: *its_feature*, *its_operation* and *its_effect*. The *its_operation* is an attribute that must be a member of an operation's list defined in a *manufacturing_feature*. The *its_effect* is an optional attribute that describes the predicted effect of the operation in the workpiece.

The entity *rapid_movement* allows the NC controller to move the tool in rapid motion to the next *workingstep* using the security plane that is also an entity. If a tool path is defined this is done using the explicit tool path instead of a controller's strategy.

Finally the entity *touch_probing* that is a base class *touch_probe workingsteps* and unlike the other *workingsteps* its main function is to return values to be used in the NC program, such as probing of the length and width/diameter of a tool and many other. The entity *nc_function* is another ABS and is used to describe operations that do not involve axes' interpolation. It may replace several miscellaneous functions, which are used in ISO 6983. It is used in operations such as display a message, stop the program until the operator restarts it, set or wait a mark in a multi channel program. Figure 5.12 defines the structure of the entity *nc_function*.

```
ENTITY nc_function
  ABSTRACT SUPERTYPE
  SUBTYPE OF (executable);
END_ENTITY;
```

Figure 5.12 -The structure of entity *nc_function* (ISO14649-10 2002).

The *program_structure* is the third type of executable object and includes other executables, which allow the flow of a program to be controlled. As written before the program structure *executables* is a class of entities that are used to control the program flow such as *while, if, parallel, and workplan.* Figure 5.13 shows the definition of the entity *program_structure.*

```
ENTITY program_structure
ABSTRACT SUPERTYPE OF (ONEOF(workplan, parallel,
non_sequential, selective, if_statement,
while_statement, assignment))
SUBTYPE OF (executable);
END_ENTITY;
```

Figure 5.13 -The entity *program_structure* (ISO14649-10 2002).

The *parallel* entity defines a set of *executables* in the attribute *branches* then the controller is allowed to run more than one executable in parallel. The entity *non_sequential* allows a set of *executables* to be executed with no order prescribed. The *selective* entity contains a set of *executable* from which only one is selected to be executed. The *if_statement* has a Boolean expression so that is dependent on whether it is true or false, one of two possible executables will be performed. The *while_statement* allows an executable to run and repeat as long as the Boolean expression is fulfilled. The entity *assignment* allows variables called *nc_variables* to be assigned values.

```
ENTITY workplan
SUBTYPE OF (program_structure);
its_elements: LIST[0:?] OF executable;
its_channel: OPTIONAL channel;
its_setup: OPTIONAL setup;
its_effect: OPTIONAL in_process_geometry;
WHERE
WR1: SIZEOF(QUERY(it <* its_elements | it = SELF)) = 0;
END_ENTITY;
```

Figure 5.14- The entity *workplan* (ISO14649-10 2002).

Finally the executable *workplan,* which is described in figure 5.14, performs the control of the sequence of execution of other executables such as *workingsteps* and *NC_function* in a linear order.

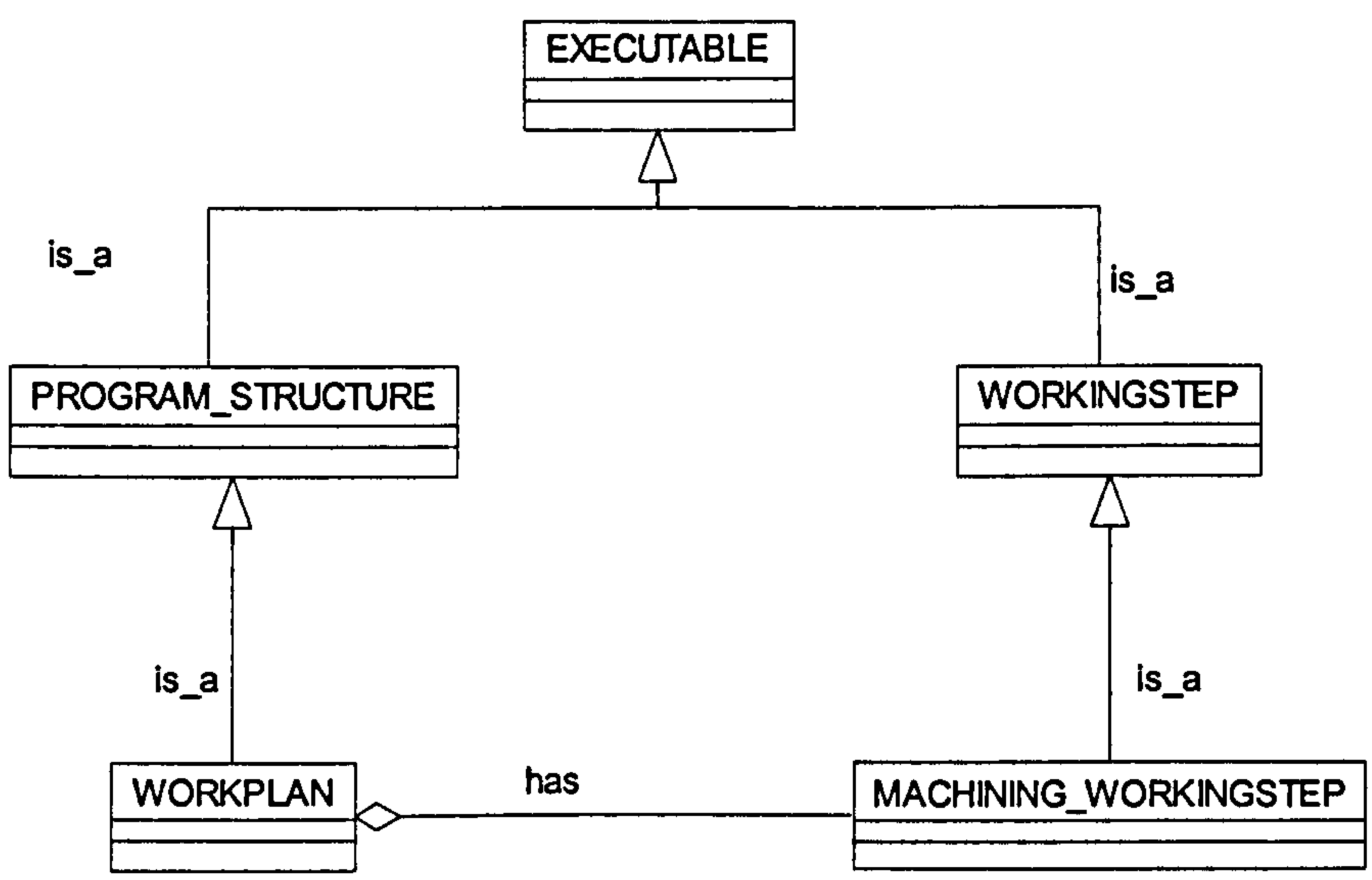
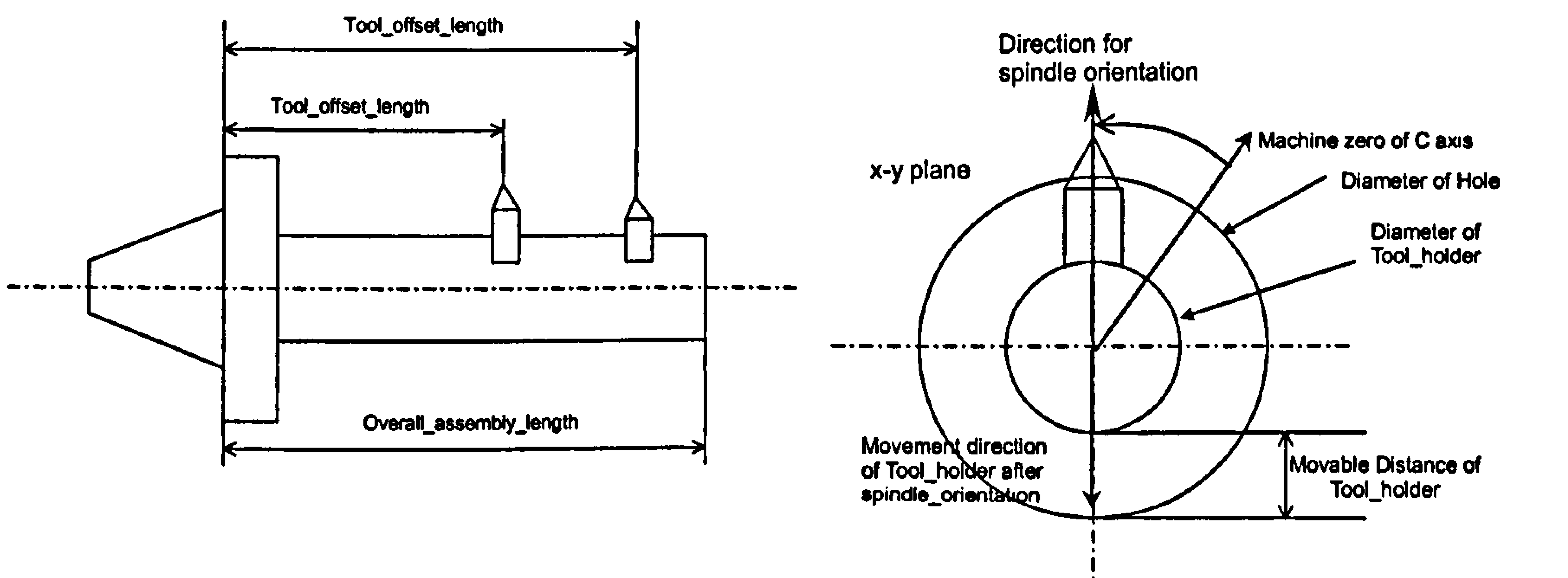


Figure 5.15- Cardinality relationship between the executables.

As identified previously, the *workplan* plays a special role in the control of the program flow. When a change is made in the sequence of *workingsteps* in a given *workplan* there is as change in the sequence, in which they are executed. Thus it is possible to achieve a change in the sequence to machining the workpiece without needing to change the whole program. These characteristics were described and addressed in the works of Schulz & Spath (1997) and Proctor & Kramer (1998). To make clear the idea of how the executables work together, figure 5.15 describes the relationship between them in terms of an object-oriented approach, for simplicity the author uses UML (Unified Modelling Language) notation. In order to describe the tools, ISO 14649 provides a class of entity called *cutting_tool.* Figure 5.16 shows the definition of cutting tool in ISO 14649-10 and figure 5.17 describes physically the parameters.

```
ENTITY cutting_tool
ABSTRACT SUPERTYPE
SUBTYPE OF (machining_tool);
its_tool_body: tool_body;
its_cutting_edge: LIST [1:?] OF cutting_component;
overall_assembly_length: OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.16 - Entity cutting tool (ISO14649-10 2002)



A: Tool offset length and overall assembly length

B: Direction for spindle orientation and tool holder diameter for spindle orientation

Figure 5.17 - The cutting tool (ISO14649-10 2002)

The entity *tool_body* is the base class defined as an ABS in Part 10 of the Standard. It is used in the technologies parts related with tools, to create instances of this object and has no parameters.

In the following items the use of the parts specific to milling and turning technologies are outlined, at present only milling machining is available as a International Standard, the turning machining model (Part 12) is still evolving to become an International Standard.

5.7 ISO 14649 Part 11 - Process Data for Milling

This part of ISO 14649 specifies the data elements for milling machining and can be used to this operation on all types of machines such as milling machines, machining centres, or a lathe with live tools. This is the first in a set of parts where each part specifies each technology such as turning(Part 12), wire EDM(Part 13), sink EDM(Part 14), or grinding. Part 11 describes the milling schema and defines data types to represent the machining process as well as the drilling process. This schema includes milling for freeform surface and prismatic workpieces, also called 2 ½ D-milling (ISO14649-11 2002). Actually, it is in the technologies parts such as Parts 11, 12, 13, etc. where the standard defines its more detailed levels of information such as strategies, operations, and functions. The data model is based on the Milling Schema (Part 11) which uses types from the Machining Schema defined in Part 10 of ISO14649. This is possible because the entities can make references from other schemas and therefore inherit from entities defined in the referred schema. The technology-specific strategies and machining operations are the major subject of ISO 14649 Part 11 and describes entities (with their sub types) such as(ISO14649-11 2002):

a) NC functions for milling
b) Tool direction for milling (*tool_direction_for_milling*),
c) Milling machine operation (*milling_machine_operation*),
d) Approach retract strategy(*approach retract strategy*),
e) Various strategies for milling and drilling,
f) Milling technology (*milling_technology*),
g) Milling machine functions (*milling_machine_functions*),
h) Milling type operation (*milling_type_operation*),
i) Free form operation (*free_form_operation*),
j) 2 ½D milling operation (*two5D_milling_operation*),
k) and the drilling type operation (*drilling_type_operation*).

The NC functions for milling are subtypes of the *nc_functions* entity defined in ISO 14649 part 10 (see section 5.6 figure 5.12) they inherit directly from that class thus, there is no ABS for these entities defined in part 11. These are function equivalent to some miscellaneous functions in ISO 6983, such as index pallet, index table, load tool and unload tool.

The entity *Tool_direction_for_milling* is an ABS. It is a subtype of the entity *tool_direction* defined in the ISO 14649 Part 10, and is used to define the tool orientation for free form machining. This is used to define if tilt and yaw angles are fixed or not during the machining process. The structure of this entity is depicted in figure 5.18.

```
ENTITY tool_direction_for_milling
  ABSTRACT SUPERTYPE OF (ONEOF(three_axes_tilted_tool,
   five_axes_var_tilt_yaw, five_axes_const_tilt_yaw))
  SUBTYPE OF (tool_direction);
END_ENTITY;
```

Figure 5.18 – The tool direction for milling (ISO14649-11 2002)

The ABS to define machining operations is the *milling_machining_operation* which defines two subtypes namely *milling_type_operation* and *drilling_type_operation.* Each one has its own operations such as *free_form_operations* and *two5D_milling_operation* (that means 2 ½ D milling operation) for milling, and *drilling_type_operation* for drilling. Figure 5.19 depicts the structure of the entity milling machining operation. The operations are then further detailed such as *plane_milling, side_milling, bottom_and_side_milling* which are sub-types of *two5D_milling_operation* .

```
ENTITY milling_machining_operation
ABSTRACT SUPERTYPE OF (ONEOF(milling_type_operation,
drilling_type_operation))
SUBTYPE OF (machining_operation);
  overcut_length: OPTIONAL length_measure;
WHERE
  WR1: (EXISTS(SELF.its_technology.feedrate_per_tooth) AND
  EXISTS(SELF.its_tool.its_tool_body.number_of_teeth))
  OR(NOT(EXISTS(SELF.its_technology.feedrate_per_tooth)));
END_ENTITY;
```

Figure 5.19 - The entity milling machining operation (ISO14649-11 2002)

The milling technology (*milling_technology*) provides the technological parameters such as cutting speed, feed rate, synchronization of the spindle with the feed, and the possible use of an adaptive control algorithm as depicted in figure 5.20.

```
ENTITY milling_technology
   SUBTYPE OF (technology);
   cutspeed: OPTIONAL speed_measure;
   spindle: OPTIONAL rot_speed_measure;
   feedrate_per_tooth: OPTIONAL length_measure;
   synchronize_spindle_with_feed: BOOLEAN;
   inhibit_feedrate_override: BOOLEAN;
   inhibit_spindle_override: BOOLEAN;
   its_adaptive_control: OPTIONAL adaptive_control;
WHERE
  WR1: (EXISTS(cutspeed) AND NOT EXISTS(spindle))
  OR (EXISTS(spindle) AND NOT EXISTS(cutspeed))
  OR (EXISTS(its_adaptive_control));
  WR2: (EXISTS(SELF.feedrate) AND NOT EXISTS(feedrate_per_tooth))
  OR (EXISTS(feedrate_per_tooth) AND NOT EXISTS(SELF.feedrate))
  OR (EXISTS(its_adaptive_control));
END_ENTITY;
```

Figure 5.20 - Definition of milling technology entity (ISO14649-11 2002)

The milling machine functions (*milling_machine_functions*) provide a description of the state of the machine functions during the operations. Functions such as switch the coolant on/off, chip removal, measure of coolant pressure, the oriented stop of spindle are defined. It can replace many tasks performed by the miscellaneous (M codes) functions in the ISO 6983 standard.

The milling type operation (*milling_type_operation*) is a base class to all milling operations and has the attribute *approach* that means the type of strategy used in the approach of the cutting tool to the workpiece. There is also an attribute *retract* which is the type of strategy used to retract the cutting tool after the finish of a cut operation. These two attributes use the entities defined in the ABS *approach_retract_strategy* which are respectively *plunge_strategy*, *air_strategy*, *along_path*. Figure 5.21 depicts four types of plunge strategy provided. The approach retract strategies are important as they are used not only for milling but also for turning operations (turning operation are described in section 5.9).

Most of the document is about the strategies for milling and drilling operation. Apart from the plunge strategy, there are further examples of how the standard defines strategies, and some of them will be shown such as the plane cutter strategy (*plane_cc_strategy*), the 2½D milling strategy (*two5D_milling_strategy*), and the drilling type strategy (*drilling_type_strategy*).

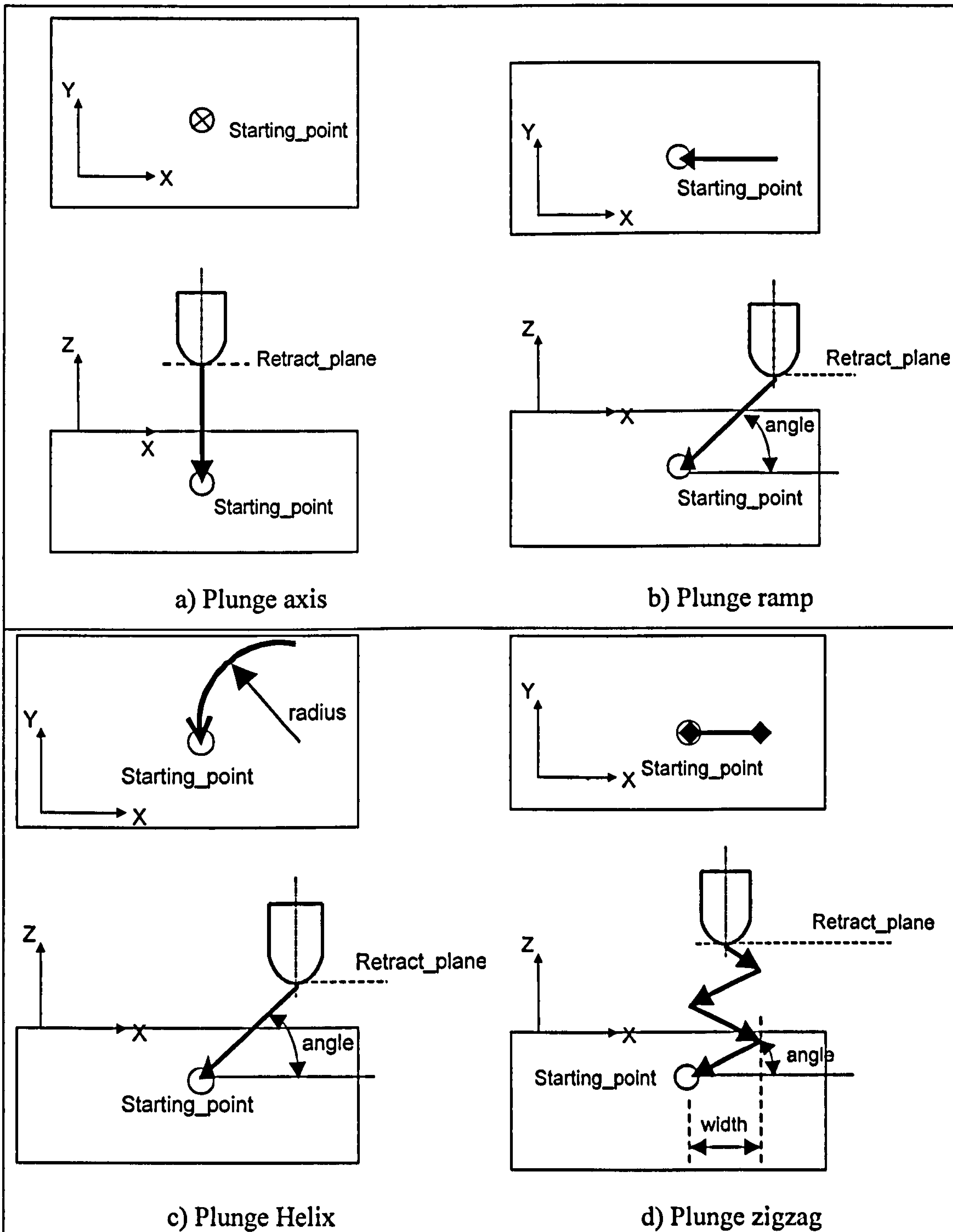


Figure 5.21 – Types of plunge strategy (Adapted from ISO14649-11 2002)

The *plane_cc_strategy* defined in figure 5.22 is used in the freeform operation (*freeform_operation*) and allows the tool motion using the intersection of parallel planes and surface to be generated, which results in the tool path. Figure 5.23 illustrates how the strategy generates the tool path, and the tool contact point with the free form surface generated.

```
ENTITY plane_cc_strategy
      SUBTYPE OF (freeform_strategy);
      its_plane_normal: direction;
END_ENTITY;
```

Figure 5.22 - Definition of entity Plane cutter contact strategy (ISO14649-11 2002)

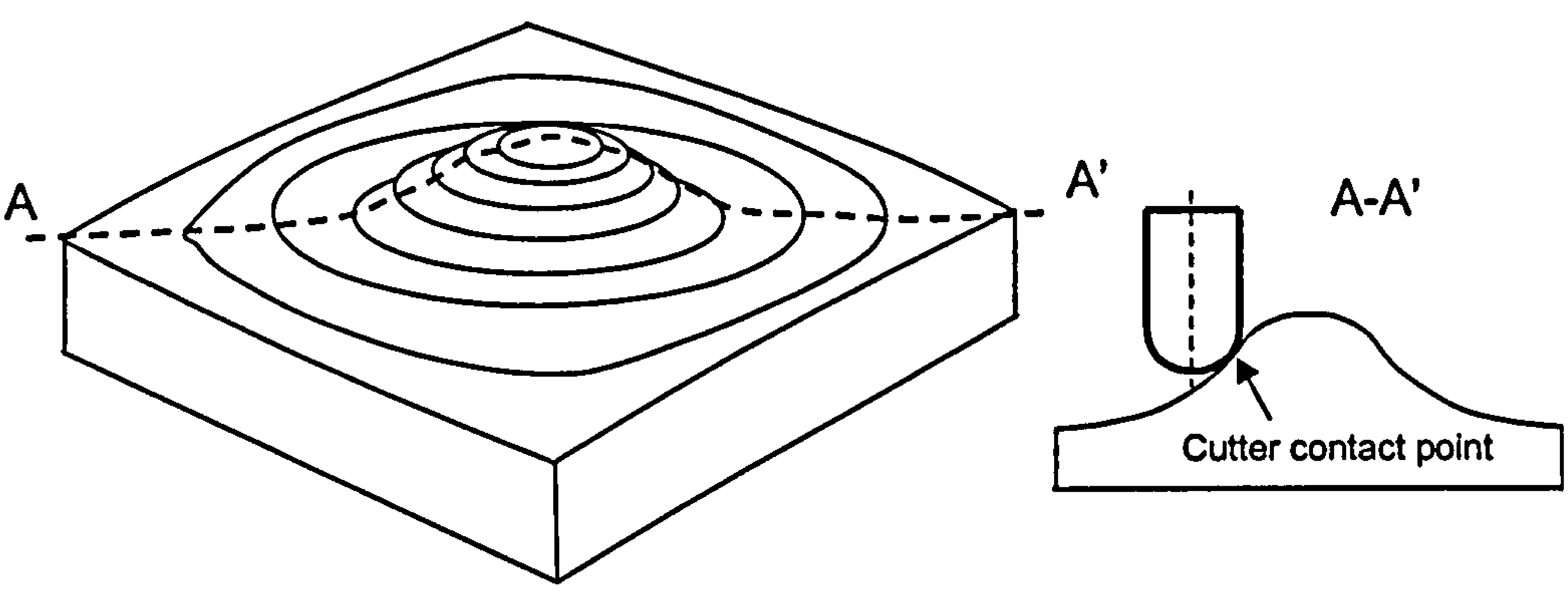


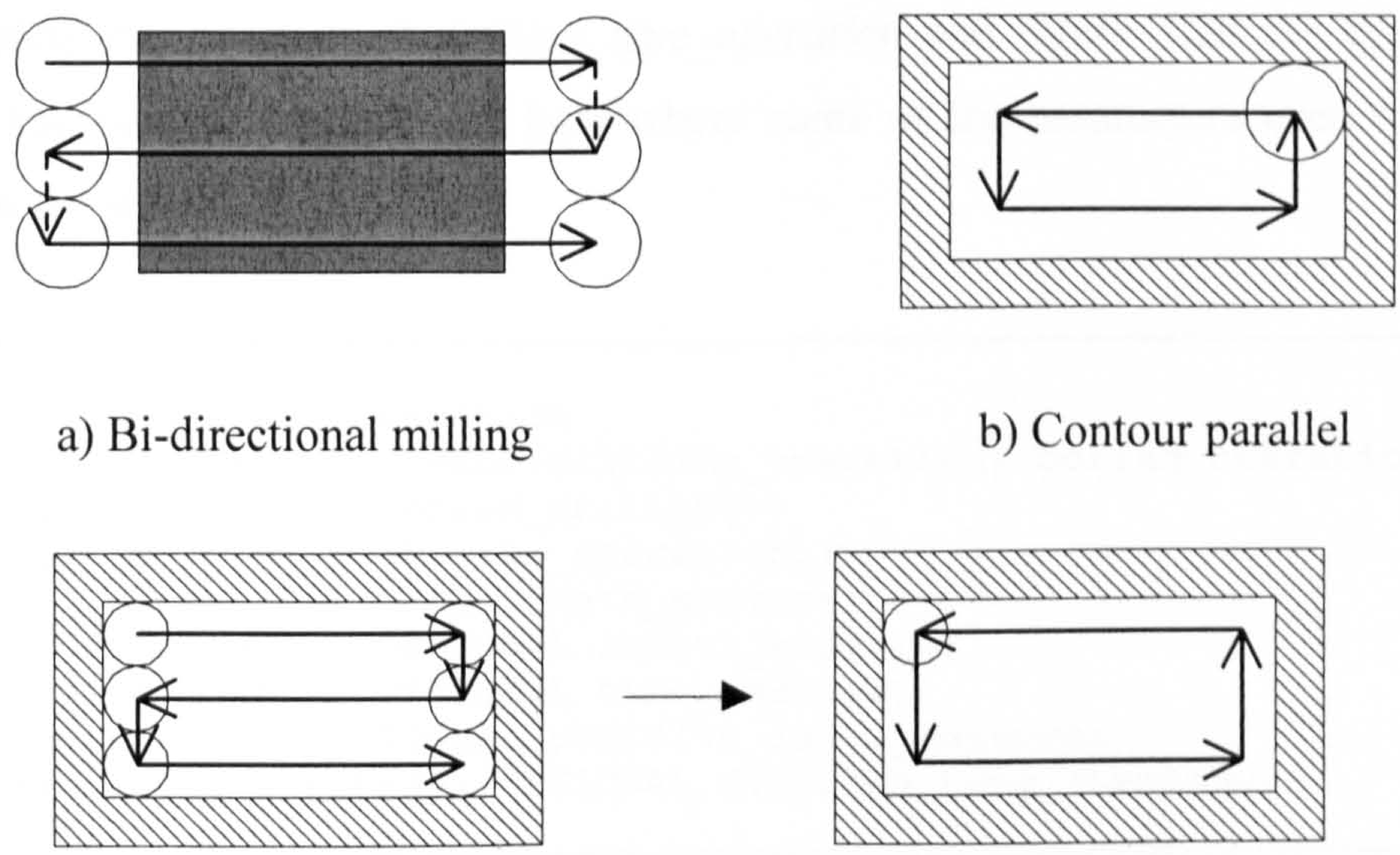
Figure 5.23 – The plane cutter contact strategy (ISO14649-11 2002)

The basic strategy to create 2 ½ D tool paths is the *two5D_milling_strategy* it provides eight strategies to milling operations. The tool path may be linear (unidirectional or bi-directional) generally for facing, in contouring (in parallel, bi-directional, and spiral), centred in the tool, and a generic path explicitly defined. Figure 5.24 depicts the structure of *two5D_milling_strategy* where is defined the subtypes which provides the tool paths and the possibility of the tool motion overlapping the last movement and multiple passes.

```
ENTITY two5D_milling_strategy
ABSTRACT SUPERTYPE OF (ONEOF (unidirectional_milling,
   bidirectional_milling, contour_parallel, bidirectional_contour,
   contour_bidirectional, contour_spiral, center_milling,
   explicit_strategy));
   overlap: OPTIONAL positive_ratio_measure;
   allow_multiple_passes: OPTIONAL BOOLEAN;
END_ENTITY;
```

Figure 5.24 - The 2 ½ D milling strategy (ISO14649-11 2002)

Figure 5.25 shows some of the milling strategies provided by the *two5D_milling_strategy* for linear and contouring paths together with the capability for combined contour and bi-directional machining.



a) Bi-directional milling   b) Contour parallel

c) Bi-directional and contour milling

Figure 5.25 – Types of milling strategies (Adapted from ISO14649-11 2002)

The *drilling_type_strategy* defined in figure 5.26 is used to provide a higher control of feed and cutting speed along the movement of the tool path in drilling operations.

```
ENTITY drilling_type_strategy;
  reduced_cut_at_start: OPTIONAL positive_ratio_measure;
  reduced_feed_at_start: OPTIONAL positive_ratio_measure;
  depth_of_start: OPTIONAL length_measure;
  reduced_cut_at_end: OPTIONAL positive_ratio_measure;
  reduced_feed_at_end: OPTIONAL positive_ratio_measure;
  depth_of_end: OPTIONAL length_measure;
WHERE
WR1: EXISTS(depth_of_start) OR NOT (EXISTS(reduced_cut_at_start) OR
EXISTS(reduced_feed_at_start));
WR2: EXISTS(depth_of_end) OR NOT (EXISTS(reduced_cut_at_end) OR
EXISTS(reduced_feed_at_end));
END_ENTITY;
```

Figure 5.26 – The structure of entity *drilling_type_strategy* (ISO14649-11 2002)

The *drilling* itself is a subtype of the entity *drilling_type_operation*, which is a subtype of the *milling_machining_operation*. All the related operations such as *drilling*, *boring*, *back boring*, *tapping*, and *thread* are subtypes of the ABS *drilling_type_operation*. This ABS provides the necessary attributes to perform all the drilling type operations using the technology and the strategy (drilling type strategy describe previously) for these operations. The basic attributes are the *cutting_depth* that informs the depth of the operation and the *previous_diameter* used when a previous operation has been performed and therefore describes the volume of material to be removed. It provides also optional parameters such as dwell time for the cutter to be delayed at the bottom of hole. Figure 5.27 depicts the structure of *drilling_type_operation* and figure 5.28 the operation in a through hole and in a pre-drilled hole where some of the parameters used to define the operation are shown.

```
ENTITY drilling_type_operation
ABSTRACT SUPERTYPE OF (ONEOF(drilling_operation, boring_operation,
back_boring, tapping, thread_drilling))
SUBTYPE OF (milling_machining_operation);
   cutting_depth: OPTIONAL length_measure;
   previous_diameter: OPTIONAL length_measure;
   dwell_time_bottom: OPTIONAL time_measure;
   feed_on_retract: OPTIONAL positive_ratio_measure;
   its_machining_strategy: OPTIONAL drilling_type_strategy;
END_ENTITY;
```

Figure 5.27 – Structure of the drilling type operation (ISO14649-11 2002)

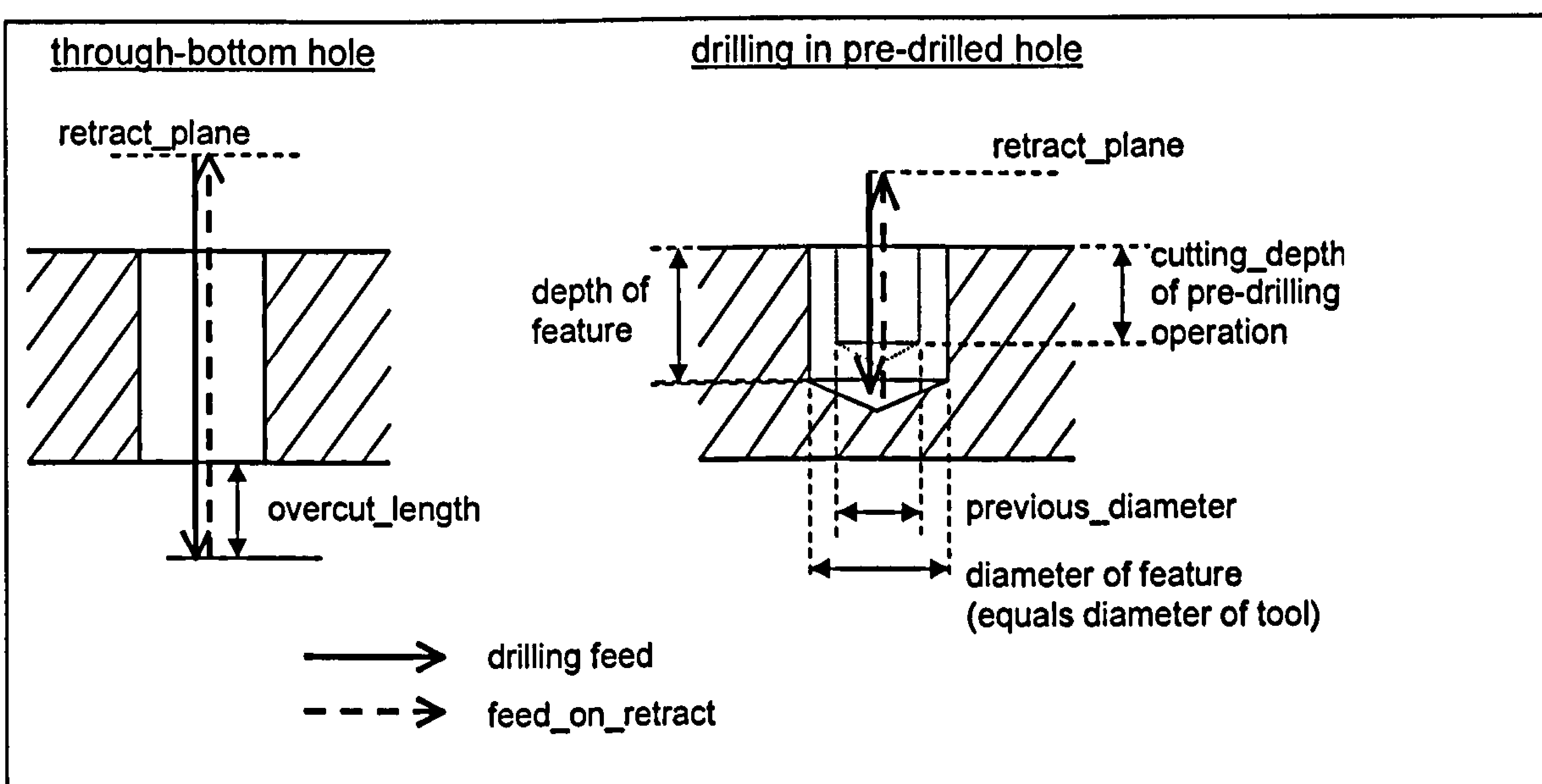


Figure 5.28 – The drilling operation parameters in through hole and in a pre-drilled hole (ISO14649-11 2002)

As a way of showing how the standard treats operations, the diagram in figure 5.29 describes the relationship between the drilling operation (*drilling_operation*) and the ABS *operation* in the author's point of view. Here the author treats the entities in an object oriented fashion. All the entities are defined in ISO 14649-11 and inherit attributes from the *machining_operation* entity, defined in ISO 14649-10. The operations in Part 11 of

ISO 14649 inherit the technology and other attributes from the *machining_operation* entity, defined in Part 10 of ISO 14649.

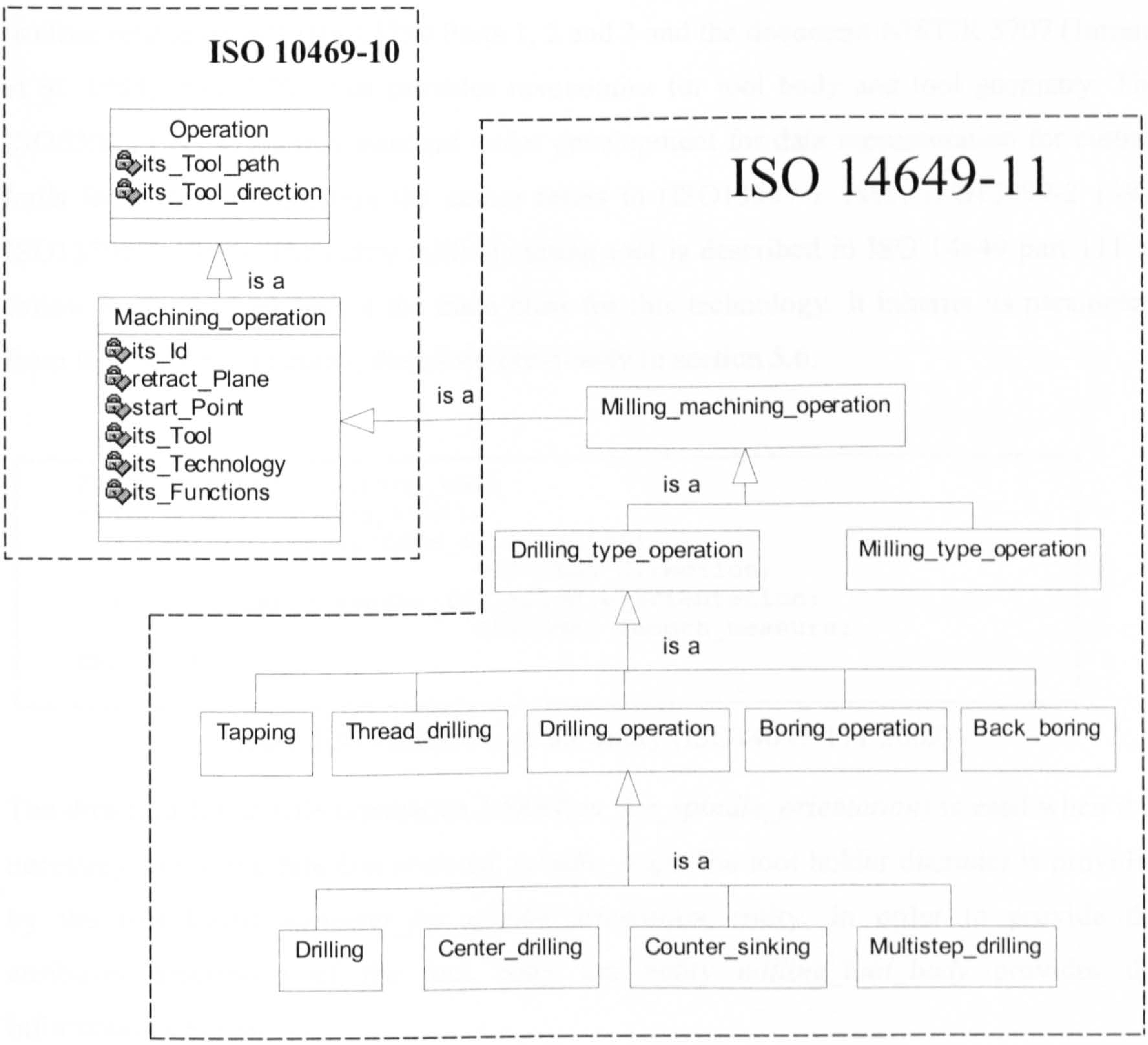


Figure 5.29 – The cardinality relationship between the Abstract Supertype *operation*, the *drilling_operation* and its subtypes

5.8 ISO 14649 Part 111 - Tools for Milling

The scope of this part is to specify a description of tools, which will be used in a given NC programme. Instead of ISO 6983, where the tool is defined using a number and the descriptions are in a separated process-sheet, in the ISO 14649 the tools are fully described as part of the program data structure. Part 111 of the standard allows the user to do that for milling process, in liaison with Part 11 and Part 10 of ISO 14649 (ISO14649-111 2002).

Any other technologies, such as turning, grinding, and EDM, should have their own parts about tools, each one in liaison with Part 10 and the part subject to its technology such as Part 12 (turning), Part 13 (EDM), etc. The Part 111 was initially written using as basis and is close related to ISO/DIS 13399 Parts 1, 2 and 3 and the document NISTIR 5707 (Jurrens et al. 1995) from NIST that provides taxonomies for tool body and tool geometry. The ISO/DIS 13399 is another standard under development for data representation for cutting tools for further information the author refers to (ISO13399-1 1999, ISO13399-2 1999, ISO13399-3 1999). The entity milling cutting tool is described in ISO 14649 part 111 as follow in figure 5.30, and is the main class for this technology. It inherits its parameters from the *cutting_tool* entity, described previously in section 5.6.

```
ENTITY Milling_cutting_tool
SUBTYPE OF (cutting_tool);
  direction_for_spindle_orientation:
                            OPTIONAL direction;
  tool_holder_diameter_for_spindle_orientation:
                            OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.30 - Structure of the entity (ISO14649-111 2002)

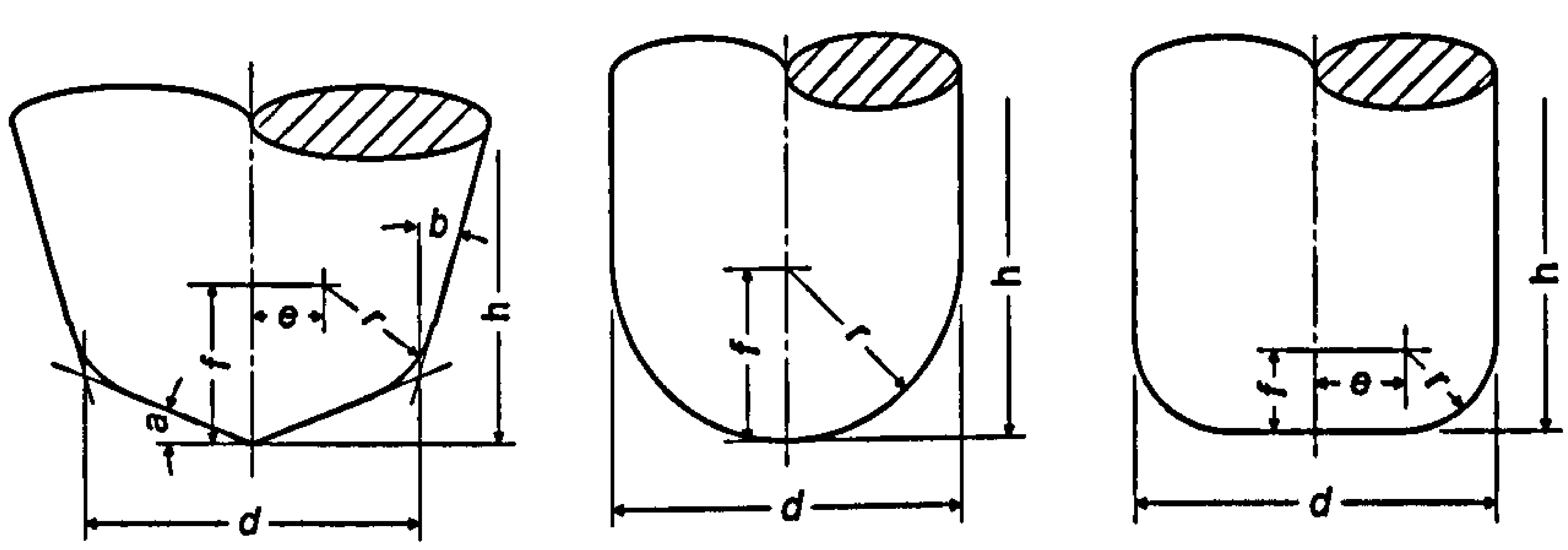
The direction for spindle orientation (*direction_for_spindle_orientation*) is used when it is necessary to use the function *oriented_spindle_stop*. The tool holder diameter is provided by the *tool_holder_diameter_for_spindle_orientation* entity. In order to provide the attributes description of the tool body the entity *milling_tool_body* provides the information such as:

a) The number of teeth (*number_of_teeth*),
b) If the tool is neutral, left or right handed (*hand_of_cut*),
c) The tool body has or not through-the-tool capability (*coolant_through_tool*),
d) The length from the tip to the sinking region(*pilot_length*)
e) and the dimension of the tool body.

The entity *milling_tool_body* has a keyhole to describe a milling tool. This is an Abstract Supertype that is used to describe the bodies of all the tools used for the milling and drilling process. Figure 5.31 depicts the structure of the entity *milling_tool_body* where it is possible to see the range of tools covered by this entity, which are centerdrill, countersink, drill, milling cutter, tap, milling threading tool, counterbore, reamer, boring tool, and an user defined tool for generic cases. The tool dimension (*tool_dimension*) is an entity that provides the dimension for different types of tools using the lengths depicted in figure 5.32. The structure of the entity *tool_dimension* is described in figure 5.33.

```
ENTITY milling_tool_body
ABSTRACT SUPERTYPE OF (ONEOF(centerdrill, countersink, drill,
milling_cutter, tap, milling_threading_tool, counterbore, reamer,
boring_tool, user_defined_tool))
SUBTYPE OF(tool_body);
   dimension: millng_tool_dimension;
   number_of_teeth: OPTIONAL INTEGER;
   hand_of_cut: OPTIONAL hand;
   coolant_through_tool: OPTIONAL BOOLEAN;
   pilot_length: OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.31 – The structure of the entity milling tool body (ISO14649 2002)



Generalised tool | Ball endmill | Bullnose endmill

d:diameter
r:edge_radius
e:edge_center_horizontal
f:edge_center_vertical h:
a:tool_tip_half_angle
b:tool_circumference_angle
h: cutting_edge_length

Figure 5.32 – The description of dimensions in the tool body (adapted from ISO14649-111 2002)

```
ENTITY milling_tool_dimension;
   diameter: length_measure;
   tool_tip_half_angle: OPTIONAL plane_angle_measure;
   tool_circumference_angle: OPTIONAL plane_angle_measure;
   cutting_edge_length: OPTIONAL length_measure;
   edge_radius: OPTIONAL length_measure;
   edge_center_vertical: OPTIONAL length_measure;
   edge_center_horizontal:OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.33 - The structure of entity *tool_dimension* (ISO 14649-111 2002)

The general structure of ISO 14649-111 covers the main characteristics of a milling tool used to set up a machine tool and, what was before (using ISO 6983) used to design a NC program. However, the current data structure covers only solid tools and there are no types of tools with indexable inserts.

5.9 ISO 14649 Part 12 - Process Data for Turning

This part of ISO 14649 is currently in the FDIS stage under the responsibility of the TC184/WC1/WG7 of the ISO standard committee. As Part 11 describes the elements of process data for milling, Part 12 does the same for turning, and can be used for lathes and turning centres. As part of its structure, ISO 14649-12 has a reference to the machining schema (*machining_schema*) defined in ISO 14649 Part 10 (see Section 5.6) that is the general data process to be referenced by specific technology (such as milling, turning, EDM, etc). The major topics of ISO 14649-12 are about the following entities:

a) Manufacturing features for turning (*turning_feature*),
b) Turning workingstep (*turning_workingstep*),
c) Turning technology (*turning_technology*),
d) Operations (*turning_machining_operation*),
e) The strategies (*turning_machining_strategy*), and
f) Machine functions (*turning_machine_functions*).

The *turning_feature* entity is defined in figure 5.34, and is the base class used for turning and is a subtype of the entity *two5D_manufacturing_feature* defined in Part 10 from where it inherits the attribute *feature_placement* that describes the position and orientation of the feature. It also inherits the attributes identifier, workpiece, and the set of operations which are in the ABS *manufacturing_feature* the superclass of *two5D_ manufacturing_feature* .

```
ENTITY turning_feature
ABSTRACT SUPERTYPE OF (ONEOF(outer_round, revolved_feature, knurl))
   SUBTYPE OF (two5D_manufacturing_feature);
END_ENTITY;
```

Figure 5.34 – The ABS turning feature (ISO14649-12 2004)

There is no mention of milling machining operations however; the entity *turning_machining_functions* has an attribute for oriented spindle stop, which allows the machine positioning of the spindle using the C-axis. Thus, it is possible to perform a complete machining (milling, out of centre drilling, etc). The features described in ISO 14649 Part 12 are turning machining features that mean they can be made using only two axes, normally Z and X. The Z axis is assumed to be a rotational axis as well. The motion in the Y axis is not defined and this position is supposed to be constant during the operation.

The three main sub-classes of turning features are the *Outer_round*, *Revolved_feature* and *Knurl*. Figure 5.35 depicts the *Turning_feature* and its subtypes using UML terminology. This part of the standard is written in total harmony with AP 224. Thus, there is no need for interpretation or mapping of ISO14649-12 in terms of AP224

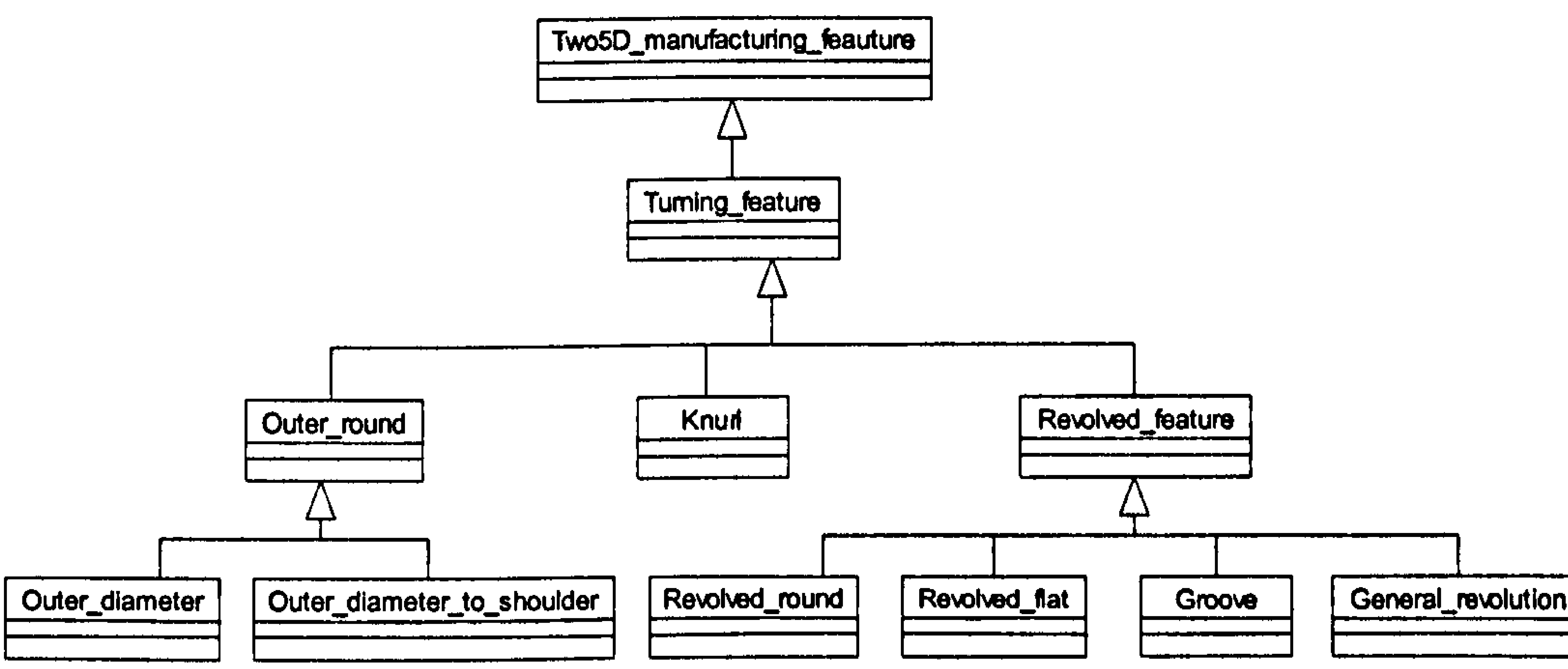


Figure 5.35 – The turning feature and its subtypes in described in UML format.

The features are well known by users in mechanical processes. For example the *Outer_diameter* in figure 5.36 which is used to describe cylinders and cones. To define a cone it is necessary just to use the *reduced_size* parameter which can be either the second diameter or the angle of the cone. Figure 5.37 shows the aspect of the *Outer_diameter* entity representing a cylinder and a cone.

```
ENTITY outer_diameter
SUBTYPE OF (outer_round);
diameter_at_placement : toleranced_length_measure;
feature_length : toleranced_length_measure;
reduced_size : OPTIONAL taper_select;
END_ENTITY;
```

Figure 5.36 – The outer diameter entity (ISO 14649-12 2004)

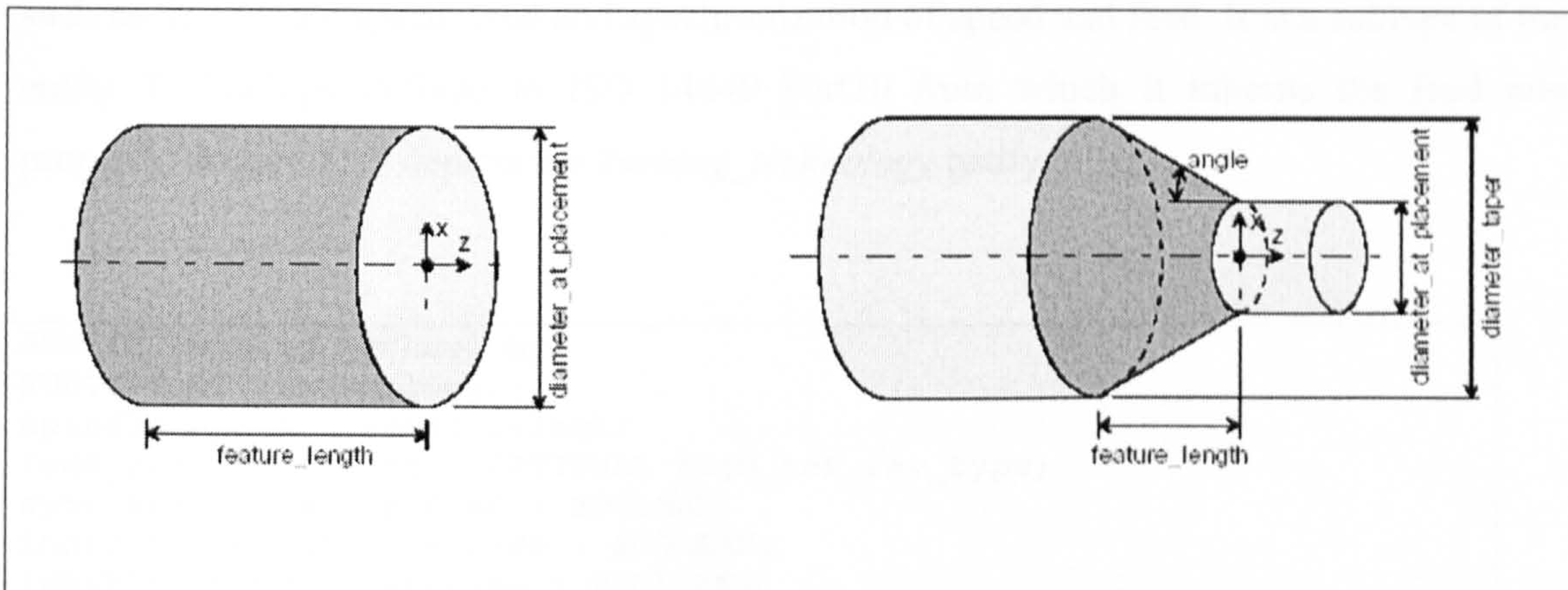


Figure 5.37 – In the left side an outer_diameter representing a cylinder and right side an outer_diameter representing a cone (ISO 14649-12 2004)

The entity *Turning_workingstep* depicted in figure 5.38 is one of the author's contributions to ISO 14649. It was created to solve the problem of machining a set of turning features in a single operation. Any single turning feature can be machined using the *Machining_workingstep*. However, the turning workpieces frequently have two or more connected turning features which should be machined in a single operation. As the *Machining_workingstep* is not allowed to perform an operation over more than one feature, the *Turning_workingstep* is defined to solve the problem of performing an operation over a list of connected features. It is a kind of *Workingstep* used to allow the rough and finishing operations over a set of connected features as happens frequently in turning operations. It can use the *Contouring* operation and the *Contour_strategy,* both from ISO 14649 Part 12, to machine the list of features. The major contribution of the use of LIST(see figure 5.38) in the *Turning_workingstep* is to provide a workingstep that can machine the contour of a collection of features without the need to define this contour nor to create a compound feature.

```
ENTITY turning_workingstep
SUBTYPE OF (workingstep);
its_features : LIST [2:?] OF manufacturing_feature;
its_operation : turning_machining_operation;
its_effect : OPTIONAL in_process_geometry;
END_ENTITY;
```

Figure 5.38 – The entity Turning_workingstep(ISO 14649-12 2004)

The *Turning_technology* is used to define technological parameters in turning operations such as the spindle speed, feed and synchronization of speed and feed. It is a subtype of the entity Technology defined in ISO 14649 Part10 from which it inherits the feed rate property. Figure 5.39 depicts the *Turning_technology* entity.

```
ENTITY turning_technology
SUBTYPE OF (technology);
spindle_speed : speed_select;
feed_per_revolution : OPTIONAL feed_per_rev_type;
sync_spindle_and_z_feed : BOOLEAN;
inhibit_feedrate_override : BOOLEAN;
inhibit_spindle_override : BOOLEAN;
its_adaptive_control : OPTIONAL adaptive_control;
WHERE
WR1: (EXISTS(SELF.feedrate) AND NOT EXISTS
(SELF.feedrate_per_revolution)) OR(NOT EXISTS(SELF.feedrate) AND
EXISTS(SELF.feedrate_per_revolution));
END_ENTITY;
```

Figure 5.39 – The entity *turning_technology*(ISO 14649-12 2004)

The operations in the turning model are represented by the base class *turning_machining_operation*, which is described in figure 5.40. It is a subtype of the entity *Operation* defined in ISO 14649-10. The drilling and milling type operations can be used in a turning program by referencing the respective operations in the ISO 14649-11(see section 5.7). When used in a *Turning_workingstep* the attribute start point refers to the first feature in the parameter LIST of the *Turning_workingstep*(ISO14649-12 2004). The operations can be either for roughing or finishing and are divided in five types which are Facing, Grooving, Contouring, Threading and Knurling. The figure 5.41 depicts the *Grooving* operation.

```
ENTITY turning_machining_operation
ABSTRACT SUPERTYPE OF (ONEOF(facing, grooving, contouring, threading,
knurling))
SUBTYPE OF (machining_operation);
approach : OPTIONAL approach_retract_strategy;
retract : OPTIONAL approach_retract_strategy;
its_machining_strategy : OPTIONAL turning_machining_strategy;
END_ENTITY;
```

Figure 5.40 – The entity turning machine operation (ISO 14649-12 2004)

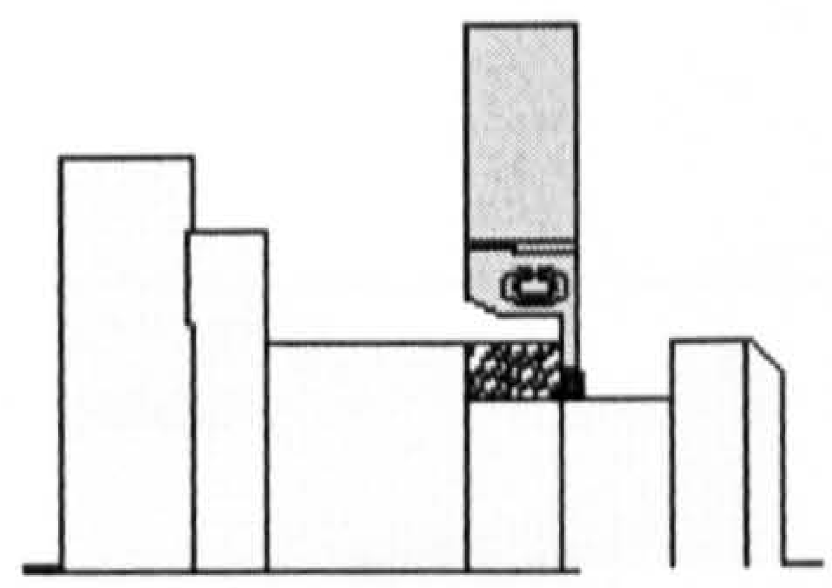


Figure 5.41 - Grooving operation (ISO14649-12 2004)

The ISO 146499 Part 12 (2004) defines six turning machining strategies which are subtypes of the *machining_strategy* defined in ISO 14649-10. They are used to create the turning tool path. Figure 5.42 depicts the *Turning_machining_strategy* and figure 5.43 shows the example of *Unidirectional_turning* using the Z direction feed.

```
ENTITY turning_machining_strategy
ABSTRACT SUPERTYPE OF (ONEOF (unidirectional_turning,
bidirectional_turning, thread_strategy, contour_turning,
grooving_strategy,explicit_turning_strategy));
overcut_length : OPTIONAL length_measure;
allow_multiple_passes : OPTIONAL BOOLEAN;
cutting_depth : LIST[0:?] OF length_measure;
variable_feedrate : OPTIONAL positive_ratio_measure;
END_ENTITY;
```

Figure 5.42 – The Turning_machinig_strategy(ISO 14649-12 2004)

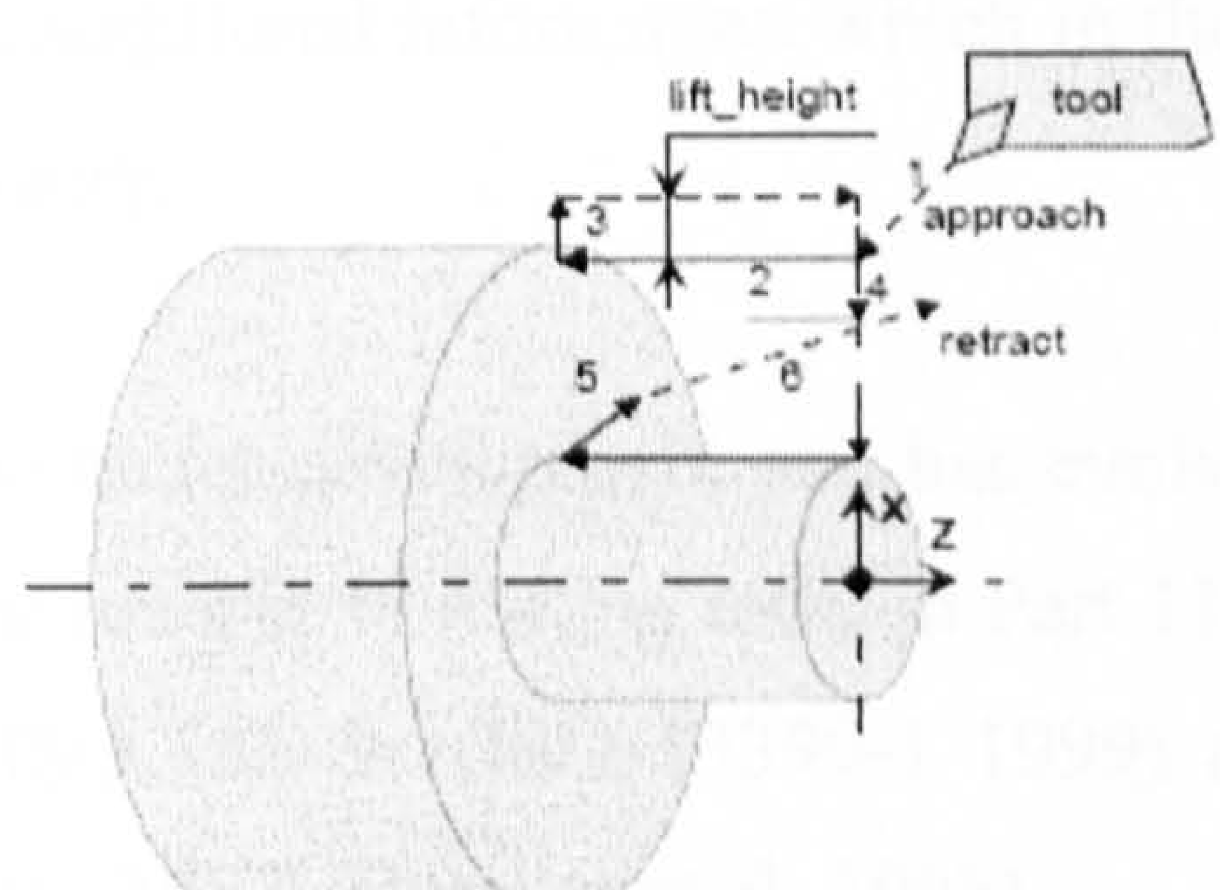


Figure 5.43 – The unidirectional turning strategy using feed direction Z (ISO 14649-12 2004)

The Machine functions are represented by the entity *turning_machine_functions* that describes various functions of the machine-tool such as the use of coolant and start the chip removal. The entity is described in figure 5.44 which shows that many of the parameters are similar to the Miscellaneous (M) functions in ISO 6983.

```
ENTITY turning_machine_functions
SUBTYPE OF (machine_functions);
coolant : BOOLEAN;
coolant_type : OPTIONAL coolant_select;
coolant_pressure : OPTIONAL pressure_measure;
axis_clamping : LIST [0:?] OF identifier;
chip_removal : OPTIONAL BOOLEAN;
oriented_spindle_stop : OPTIONAL direction;
its_process_model : OPTIONAL process_model_list;
other_functions : SET [0:?] OF property_parameter;
tail_stock : OPTIONAL BOOLEAN;
steady_rest : OPTIONAL BOOLEAN;
follow_rest : OPTIONAL BOOLEAN;
END_ENTITY;
```

Figure 5.44 – The entity turning machine function(ISO 14649-12 2004)

5.10 The ISO 14649 Part 121 - Tools for Turning

This section is based on the ISO14649-121(2003) from February 2003. There are later versions in 2003 and 2004 (ISO14649-121 2004), but these are so different from each other that the author considers that there is no consensus on the turning tool issue and suggests that the presented version should be amalgamated with the ISO14649-121 from July 2004. Therefore, in Chapter 7 the models described were developed based on ISO14649-121 (2003) with additional information which in the author's opinion is more in line with the use in the industry.

As Part 12, Part 121 is also under development and has evolved radically during the time of this research. In a similar manner to milling tools in Part 111 (described in Section 5.8), Part 121 is based on the ISO 13399-1(ISO 13399-1 1999) and in the guidelines of the document NISTIR 5707 from NIST (Jurrens et al. 1995).

The ISO 14649-121 has explicit references to the machining schema (*machining_schema*) from where it inherits the definition of many entities. The main entities in the Part 121 are the *Turning_machine_tool* and the *Turning_machine_tool_body* entities. They are respectively subtypes of the cutting tool and tool body entities from the machining schema, which are defined in ISO 14649-10. Figure 5.45 depicts the *Turning_machine_tool* entity which has two attributes the overall assembly width and the *Minimum_cutting_diameter* which is used to define the minimum diameter of a hole in which the tool can perform an operation. The parameter overall assembly width of the tool is inherited from the *Cutting_tool* entity defined in ISO14649-10. Figure 5.46 depicts the turning tool overall assembly length, overall assembly width and the minimum cutting diameter.

```
ENTITY turning_machine_tool
SUBTYPE OF (cutting_tool);
overall_assembly_width: OPTIONAL length_measure;
minimum_cutting_diameter : OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.45 – The turning_machine_tool entity(ISO14649-121 2003)

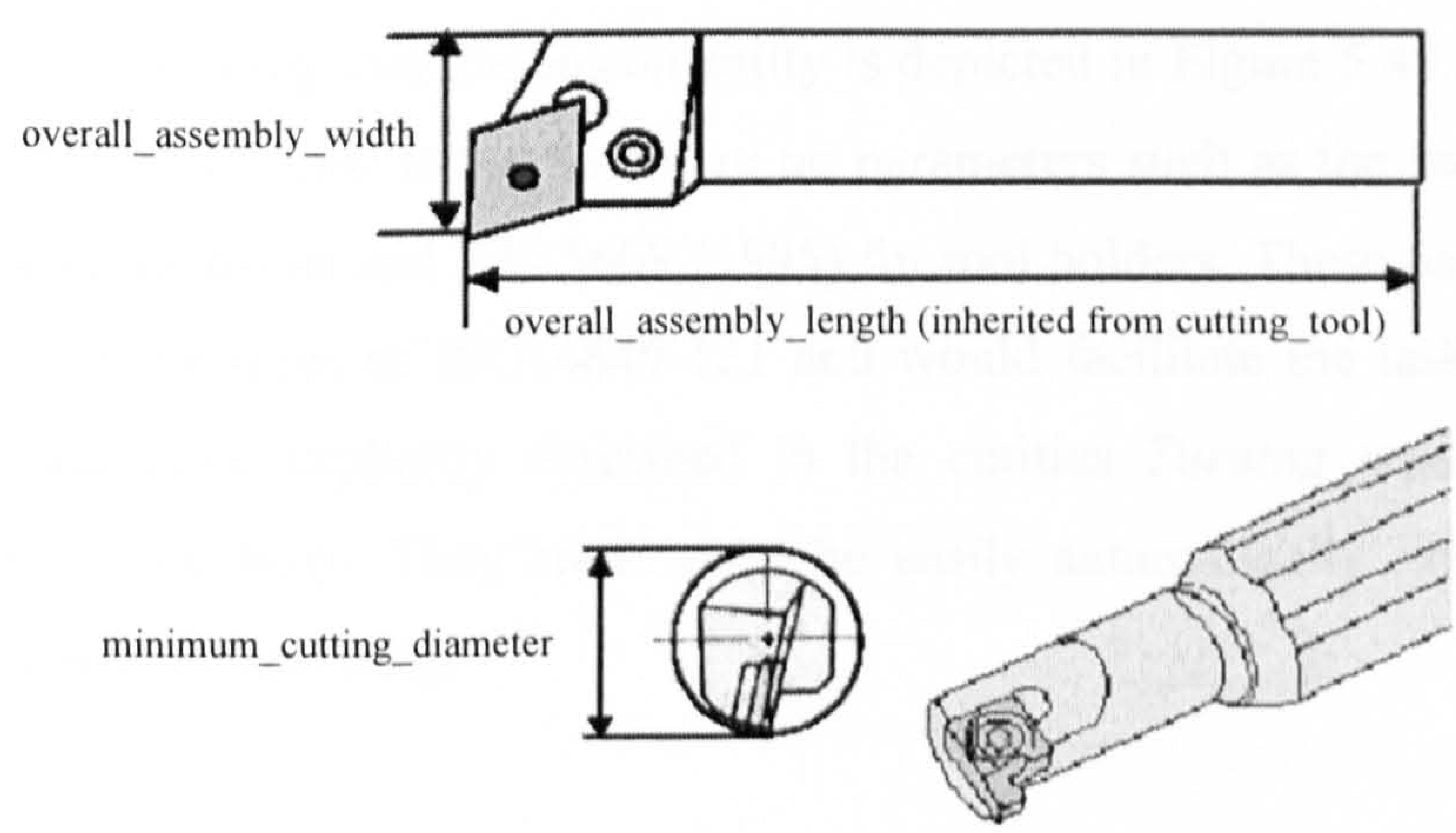


Figure 5.46 – The cutting tool assembly measures and minimum cutting diameter(ISO14649-121 2003)

The entity *Turning_machine_tool_body* is the supertype for all types of turning tools which are the *general_turning_tool*, *knurling_tool*, *turning_threading_tool*, *grooving_tool* and the *user_defined_turning_tool*. With this set of entities STEP-NC can describe most of the turning tools used in the industry. Figure 5.47 describes the *Turning_machine_tool_body* entity. The majority of the parameters in the *Turning_machine_tool_body* entity are optional with the exception of the dimension parameter defined by the *Turning_tool_dimension* entity.

```
ENTITY turning_machine_tool_body
ABSTRACT SUPERTYPE OF (ONEOF(general_turning_tool, knurling_tool,
turning_threading_tool, grooving_tool, user_defined_turning_tool));
SUBTYPE OF (tool_body);
dimension : turning_tool_dimension;
hand_of_tool : OPTIONAL hand_of_tool_type;
tool_allowance_length : OPTIONAL length_measure;
tool_body_height : OPTIONAL length_measure;
tool_body_width : OPTIONAL length_measure;
rotational_direction : OPTIONAL rot_direction;
END_ENTITY;
```

Figure 5.47 - *Turning_machine_tool_body* entity (ISO14649-121 2003)

All of the parameters in the *Turning_tool_dimension* entity are optional. However, this entity is very important as it provides important parameters for the process planning activity such as the size of the tool's nose radius and the end and side cutting edge angles. The structure of the turning tool dimension entity is depicted in Figure 5.48. One criticism from the author point of view is that there are no parameters such as the codes ISO 1832 (2004) for indexable inserts and ISO 5608 (1995) for tool holders. These parameters were present in previous versions of ISO14649-121 and would facilitate the task of providing most of the parameters explicitly described in the entities *Turning_machine_tool* and *Turning_machine_tool_body*. They could even be easily automatically interpreted as in Rosso-Jr(1995) and Boehs(1988).

```
ENTITY turning_tool_dimension;
cutting_edge_length : OPTIONAL length_measure;
end_cutting_edge_angle : OPTIONAL plane_angle_measure;
side_cutting_edge_angle : OPTIONAL plane_angle_measure;
back_rake_angle : OPTIONAL plane_angle_measure;
side_rake_angle : OPTIONAL plane_angle_measure;
side_relief_angle : OPTIONAL plane_angle_measure;
side_clearance_angle : OPTIONAL plane_angle_measure;
end_relief_angle : OPTIONAL plane_angle_measure;
end_clearance_angle : OPTIONAL plane_angle_measure;
nose_radius : OPTIONAL length_measure;
circle_diameter : OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.48 – The structure of the entity *Turning_tool_dimension* (ISO 14649-121 2003)

The subtypes of the *Turning_machine_tool_body* which are the *general_turning_tool*, *knurling_tool*, *turning_threading_tool*, *grooving_tool* and the *user_defined_turning_tool* tool types, are described in a catalogue of turning tools. Therefore, all these subtypes inherit parameters from the *Turning_machine_tool_body* of ISO14649 Part 121. Thus the general turning tool entity has the simplest structure as shown in Figure 5.49. It is used in most of the turning operation such as facing and contouring.

```
ENTITY general_turning_tool
SUBTYPE OF (turning_machine_tool_body);
END_ENTITY;
```

Figure 5.49 – Structure of the *general_turning_tool* entity (ISO14649-121 2003)

The *turning_threading_tool* entity has the parameters to describe the thread angle and the thread pitch. If the thread angle is not defined it is assumed from the Thread feature associated to the operation using the tool. If the threading angle is not provided it is assumed to be 60°. Figure 5.50 depicts the structure *turning_threading_tool.*

```
ENTITY turning_threading_tool
SUBTYPE OF (turning_machine_tool_body);
threading_pitch : length_measure;
threading_angle : OPTIONAL plane_angle_measure;
END_ENTITY;
```

Figure 5.50 – The structure of the entity *Turning_threading_tool* (ISO14649-121 2003)

The *grooving_tool* (Figure 5.51) has also two parameters the cutting width and the corner radius. This entity suffer from a lack of generality as a grooving tool can has more than one radius size.

```
ENTITY grooving_tool
SUBTYPE OF (turning_machine_tool_body);
cutting_width : length_measure;
corner_radius : OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.51 – The structure of the entity *grooving_tool* (ISO14649-121 2003)

The knurling tool has parameters to describe the type of knurl pattern used by the tool, the cutting length, the angle that the knurl pattern makes with the orientation axis of the surface where it is applied and the pitch. The knurling tool structure is depicted in Figure 5.52.

```
ENTITY knurling_tool
SUBTYPE OF (turning_machine_tool_body);
knurl_pattern_type : knurl_pattern;
cutting_length : OPTIONAL length_measure;
angle : OPTIONAL plane_angle_measure;
pitch : OPTIONAL length_measure;
END_ENTITY;
```

Figure 5.52 – The structure of the entity *grooving_tool* (ISO14649-121 2003)

Finally the *user_defined_turning_tool* has only one parameter which is the identifier.

Chapter 6

Frameworks for a STEP Compliant Turn/Mill CAD/CAPP/CAM System

6.1 Introduction

This chapter reports the author's research related to the possible implementation frameworks for STEP compliant CAD/CAPP/CAM environments. It was initially based on observations and discussions with other groups abroad made during a STEP-NC Forum at the EMO-2001 in Hanover-Germany. Based on these observations, a careful analysis of STEP-NC developments and the author's views of future needs for the industry has identified the following vision towards STEP-NC compliance. The first part describes a view of the role of STEP-NC replacing ISO 6983. The major part provides the result of an investigation on possible implementation frameworks. The final section describes the author's view on the integration of STEP compliant data models that forms the basis of the information models in this research.

6.2 A Vision Towards a Higher Level of NC Programming

As reported in Chapter 5, STEP-NC is not a programming language but a data interface for CAM/CNC programming. It can be said however, that the result is that the NC control is in fact guided by a STEP-NC compliant file which behaves as a NC program. Contrarily the ISO 6983 standard describes how the machine-tool should behave, using STEP-NC the process planner informs what should be done. Thus, it is dissociated from the intrinsic characteristics of any particular machine-tool. STEP-NC represents a major paradigm shift as currently nearly all NC programming is represented by low-level programming machine movement. In the future it is believed that a major difference will be seen at the shop floor as the operators will be able to make last minute changes in major parts of the program, by just changing parameters in a *Workingstep* or change operational sequences changing a *Workplan*. One noticeable difference to ISO 6983 is that this change will be able to be transferred up to the CAx process chain to CAD/CAM or product data management (PDM) systems and not just at the CNC machine tool.

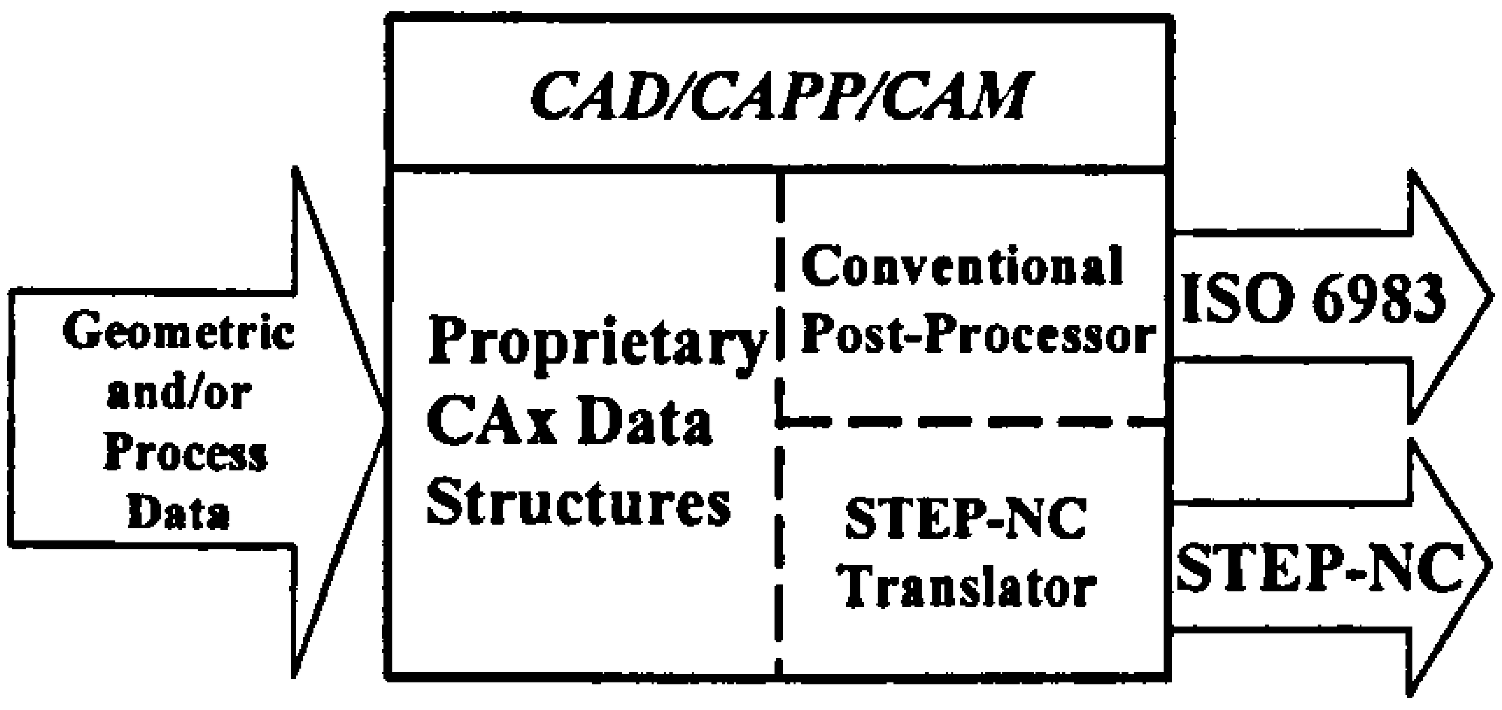
6.3 Implementation Frameworks Towards a STEP Compliant CAD/CAPP/CAM Environment

The author originally devised these frameworks as for use in CAD/CAM systems (Rosso-Jr et al. 2002). However, it is the author's belief that the differences between CAPP and CAM have been narrowed throughout the evolution of CAM systems and in particular by the emerging standard ISO 14649. As written in Chapter 5, a STEP-NC program is very similar to a process plan for NC machines written in STEP format.

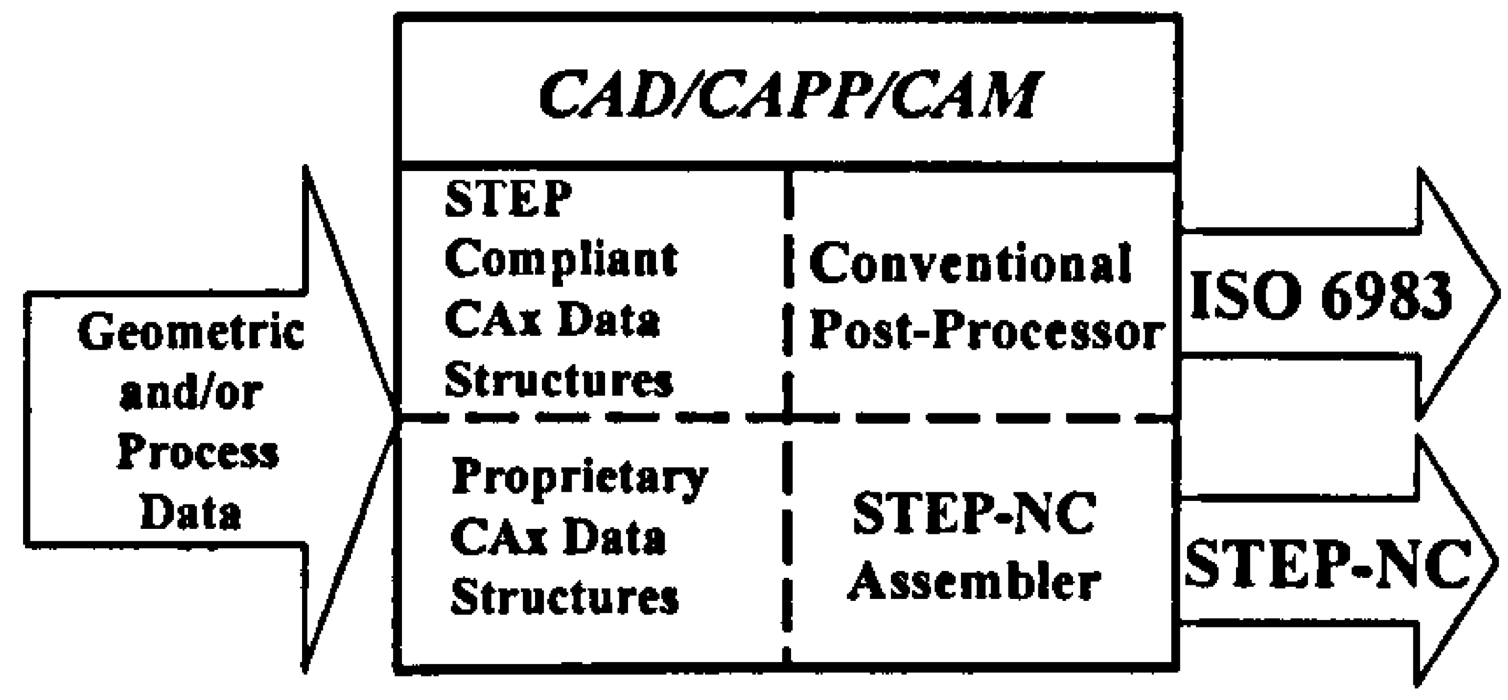
The development of ISO 14649 provides a number of options for interpretation and implementation of this standard within CAD/CAPP/CAM systems. The implementations in this thesis are defined by the author as ISO 14649 compliant, and referred to as STEP compliant NC (STEP-NC). Three frameworks are defined for STEP-NC implementation as outlined below:

i) A CAD/CAPP/CAM system which imports/generates a STEP-NC output;
ii) A CAD/CAPP/CAM systems with hybrid STEP-NC and conventional data support structures;
iii) A CAD/CAPP/CAM environment with kernel STEP-NC data structure.

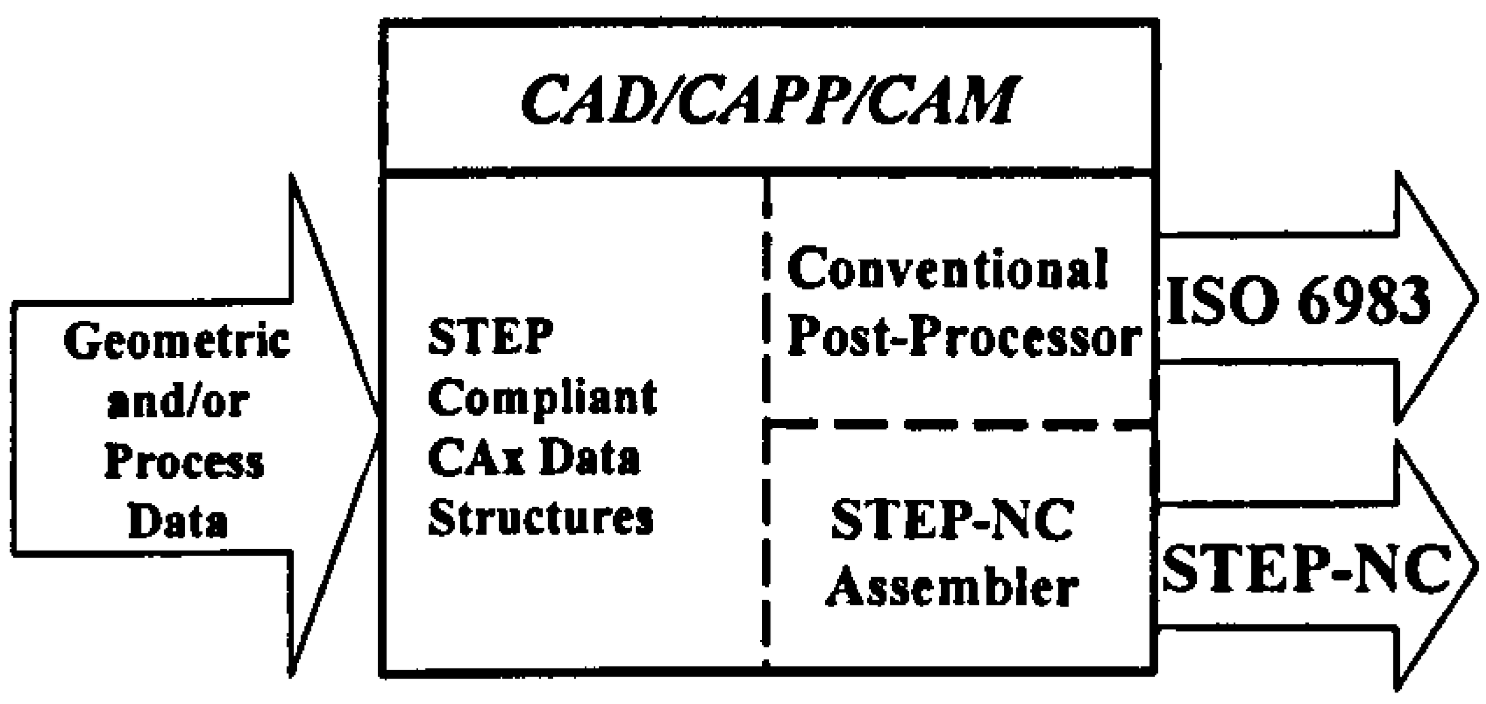
Figure 6.1 shows a schematic view of these frameworks and their differences. As in Figure 6.1a a conventional CAD/CAPP/CAM is able to read and export STEP compliant data. In figure 6.1b a hybrid conventional/STEP compliant structure supports the work of the CAx system and in figure 6.1.c where only a STEP compliant structure is used. In sections 6.3.1 to 6.3.3 these frameworks are explained in detail.



a) CAD/CAPP/CAM system which imports/generates a STEP-NC output



b) CAD/CAPP/CAM Systems with hybrid STEP and conventional data support structures;



c) CAD/CAPP/CAM environment with kernel STEP data structure

Figure 6.1 – Schematic View of Implementation Frameworks

6.3.1 A CAD/CAM System which Imports/Generates STEP-NC Information

This first form of STEP-NC framework provides a CAD/CAM System with the ability to import and generate ISO 14649 information. It is used in its normal operational form using its own native feature representation and manufacturing strategies for the design and manufacture of components. The generation of the ISO14649 output is created by mapping the native CAD/CAM information structures onto the STEP compliant data through a post processor specifically for ISO 14649. It can also import information in the ISO14649 format which is translated into the native geometric and manufacturing data structure of CAD/CAM. This framework is depicted in Figure 6.2 and has been used in the initial phases of use of ISO14649. It is predictable that some implementations would have both import and export facilities and some however, would provide only an import or export capability for transfer of information.

Example applications of this framework have been demonstrated by RWTH Aachen and ISW Stuttgart with significant focus on development of the STEP-NC compliant Siemens 840D controller. Commercial applications in Europe with CATIA and OpenMind systems have been presented by Volvo and Daimler Chrysler illustrating the capability to incorporate the standard within the CAD/CAM products and export the STEP-NC output to the Siemens 840D controller(Weck & Wolf 2003). In addition to STEP-NC milling developments the technology has also been extended to CNC turning. This has been achieved with the prototype STEPTurn software module developed by ISW Stuttgart, and the Siemens 840 control on a Boehringer NG200 lathe (Heusinger et al. 2005). The STEPTurn software imports CAD geometry and recognised features, allowing the definition of machining strategies and technologies and generated STEP-NC output. The Siemens controller receives this output and converts it into the Siemen's ShopTurn system via a STEP-NC import facility.

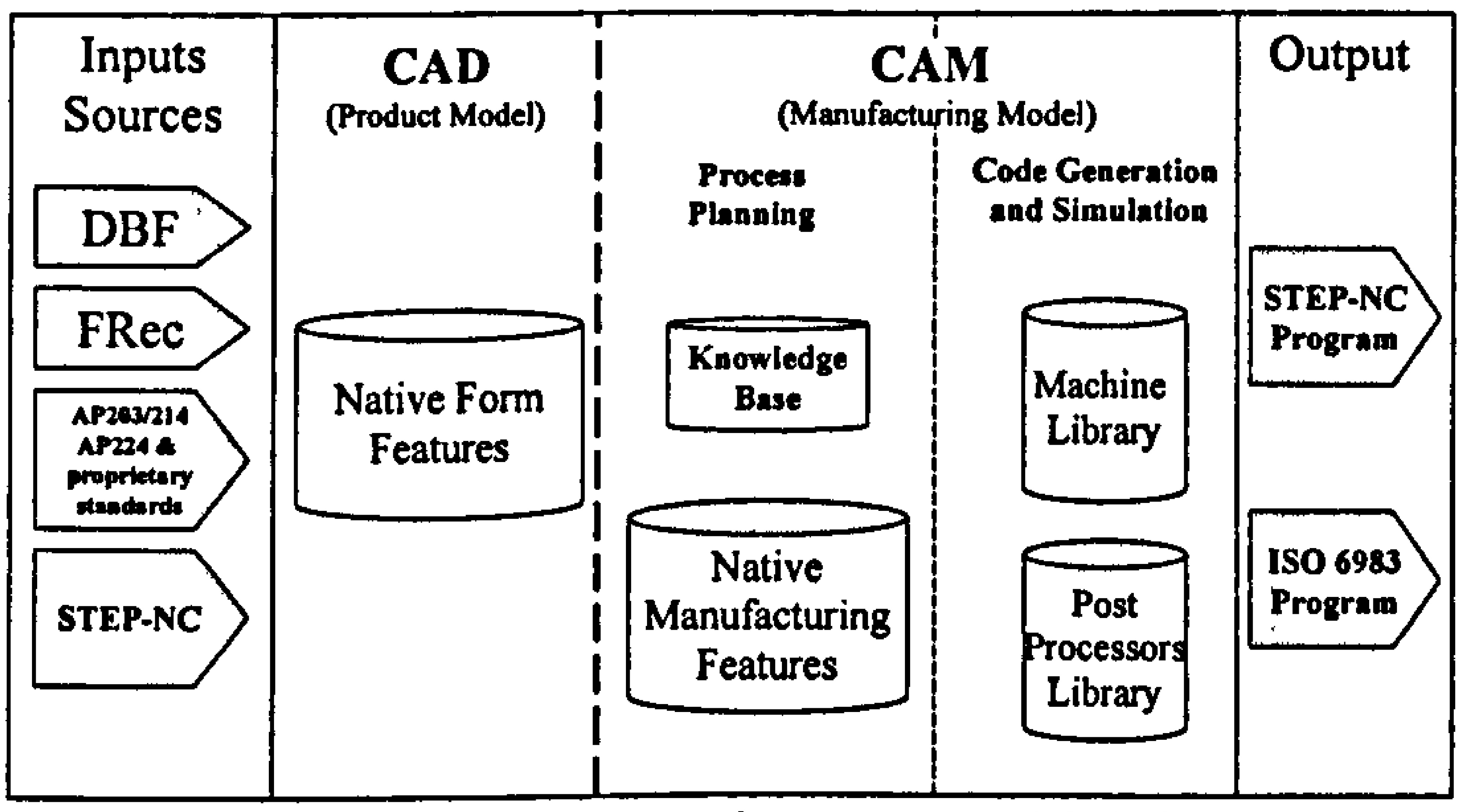


Figure 6.2 – CAD/CAM environment which imports and generates STEP compliant data

6.3.2 A CAD/CAM System with STEP-NC Data Support Structures

This framework is classified by the CAD/CAM system having a STEP-NC data support structure that may be held internally or externally to the CAD/CAM system. Two variants of this framework are outlined below.

6.3.2.1 A CAD/CAM system integrated with an external STEP-NC data support system

In this case, the CAD/CAM system is integrated with an external software system to provide the STEP compliant data management support. The framework illustrated in figure 6.3, shows the CAD/CAM system functioning independently to a STEP-compliant data management system. This is used not only for importing information and generating

STEP-compliant code, but also in interpreting the native CAD/CAM geometric and manufacturing routines. In addition it has STEP-compliant workplans and greater control to configure the output compared to using the solutions represented in section 6.3.1.

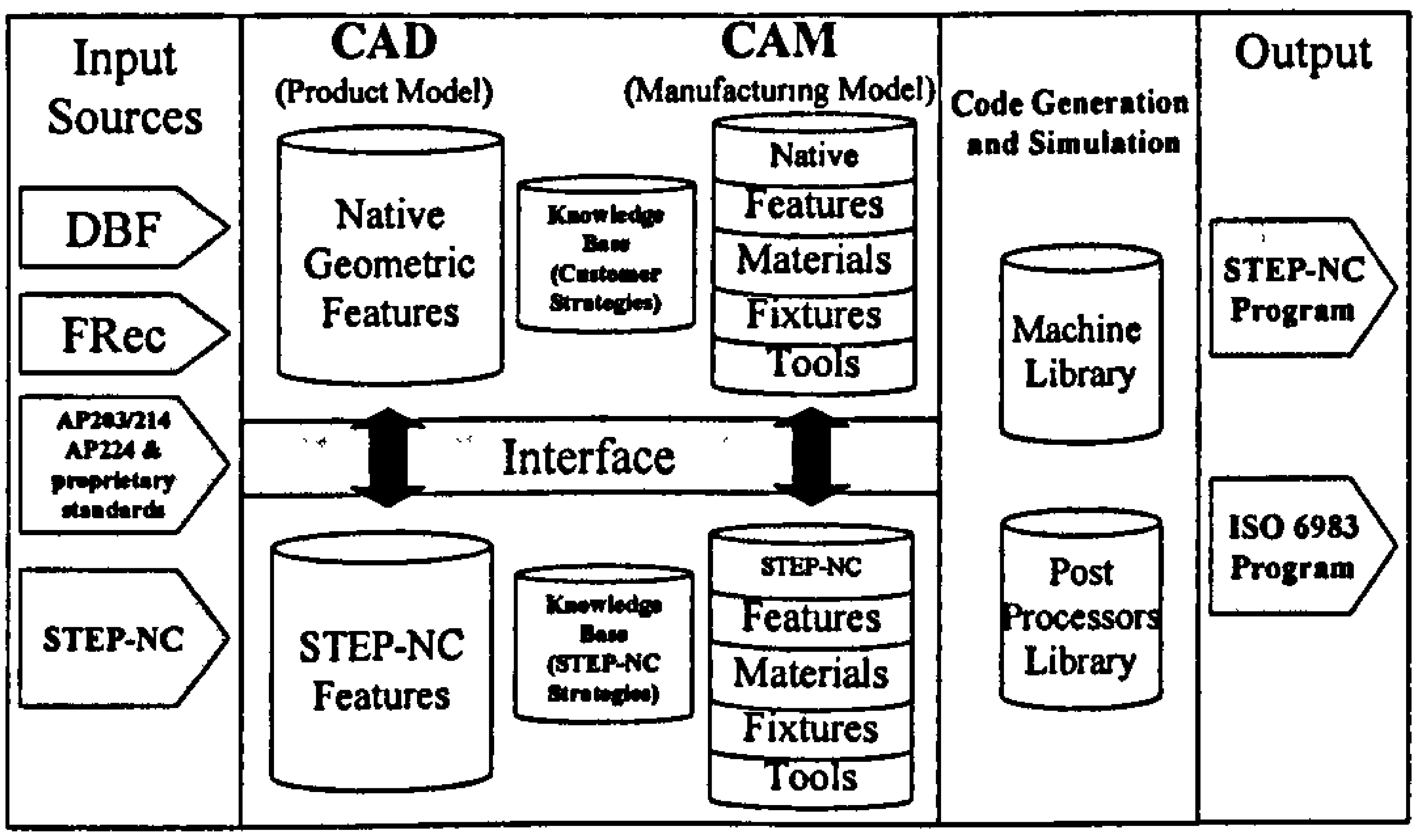


Figure 6.3 – CAD/CAM environment with both native and STEP compliant external data structure

6.3.2.2 A CAD/CAM environment with both native and STEP-NC internal data structures

This case represents a CAD/CAM system, which has a dual internal representation of geometric and manufacturing data, both in the native format of the CAD/CAM system and in the ISO 14649 format.

Thus in the operational use of the system both sets of data are updated in real time rather than generating the STEP output through a post processor or having the STEP information structures in an external software environment. Although this framework has essentially the same principle as in 6.3.2.1, it represents a significant improvement since no post-processing is required to generate STEP-NC code. This framework is illustrated in figure 6.4.

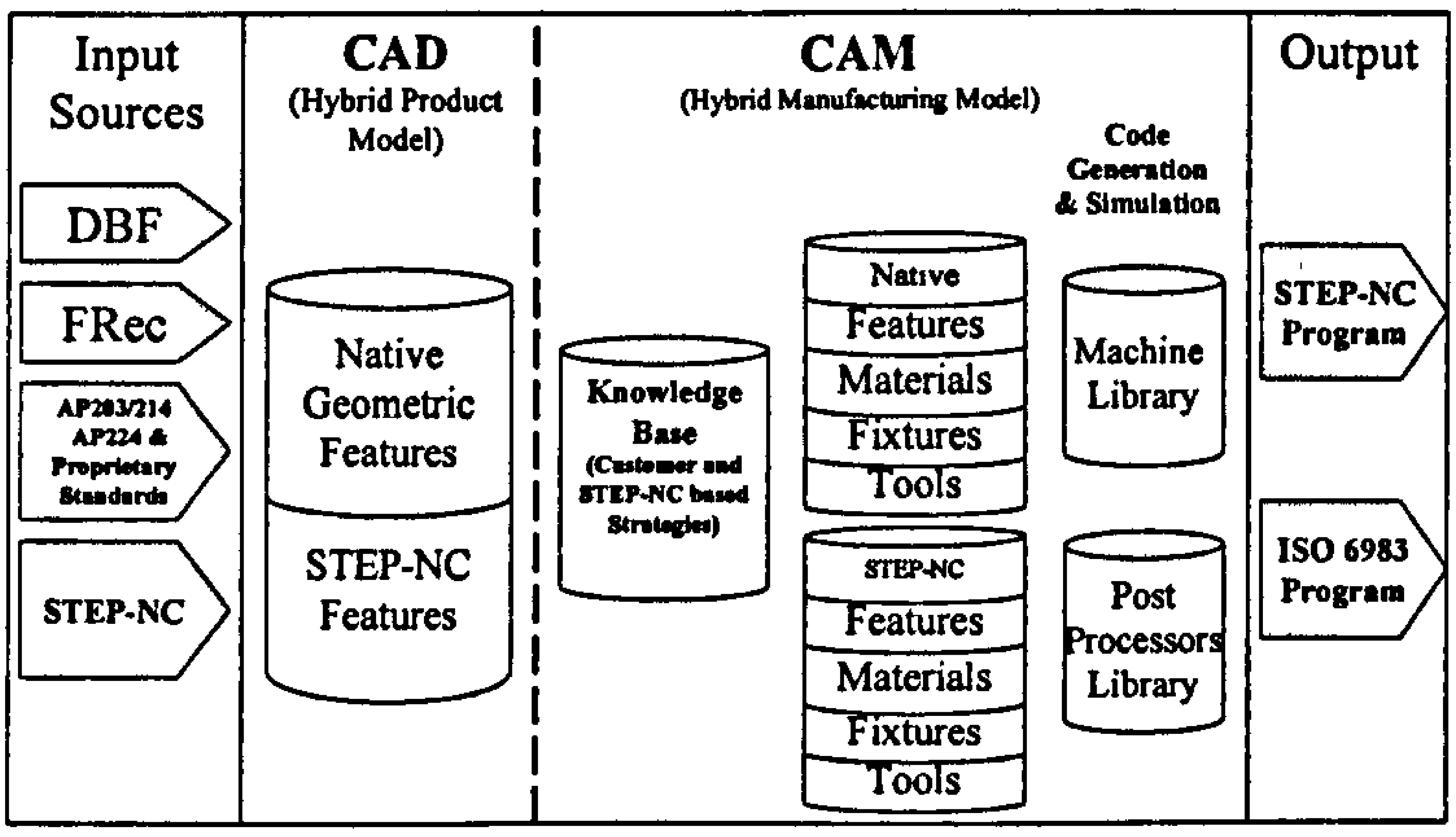


Figure 6.4 – CAD/CAM environment with both native and STEP compliant internal data structure

6.3.3 A CAD/CAM Environment with Kernel STEP-NC Data Structure

This research work is focused on this highest level of compliance which is based on a CAD/CAM environment, which uses ISO 14649 and ISO 10303-224 for both geometric and manufacturing data models. The author believes that this structure will form the basis of new developments for CAD/CAM vendors and will also provide the direct and simplest generation of ISO 14649 NC code. One overhead of this framework will be the need to post process the STEP data into ISO 6983 G/M code output for conventional CNC controllers during a transition period when both standards will be in use.

In this research work, the realization view point which consists of the design of information models, related user interfaces and their application to an asymmetric rotational part is based on this third framework

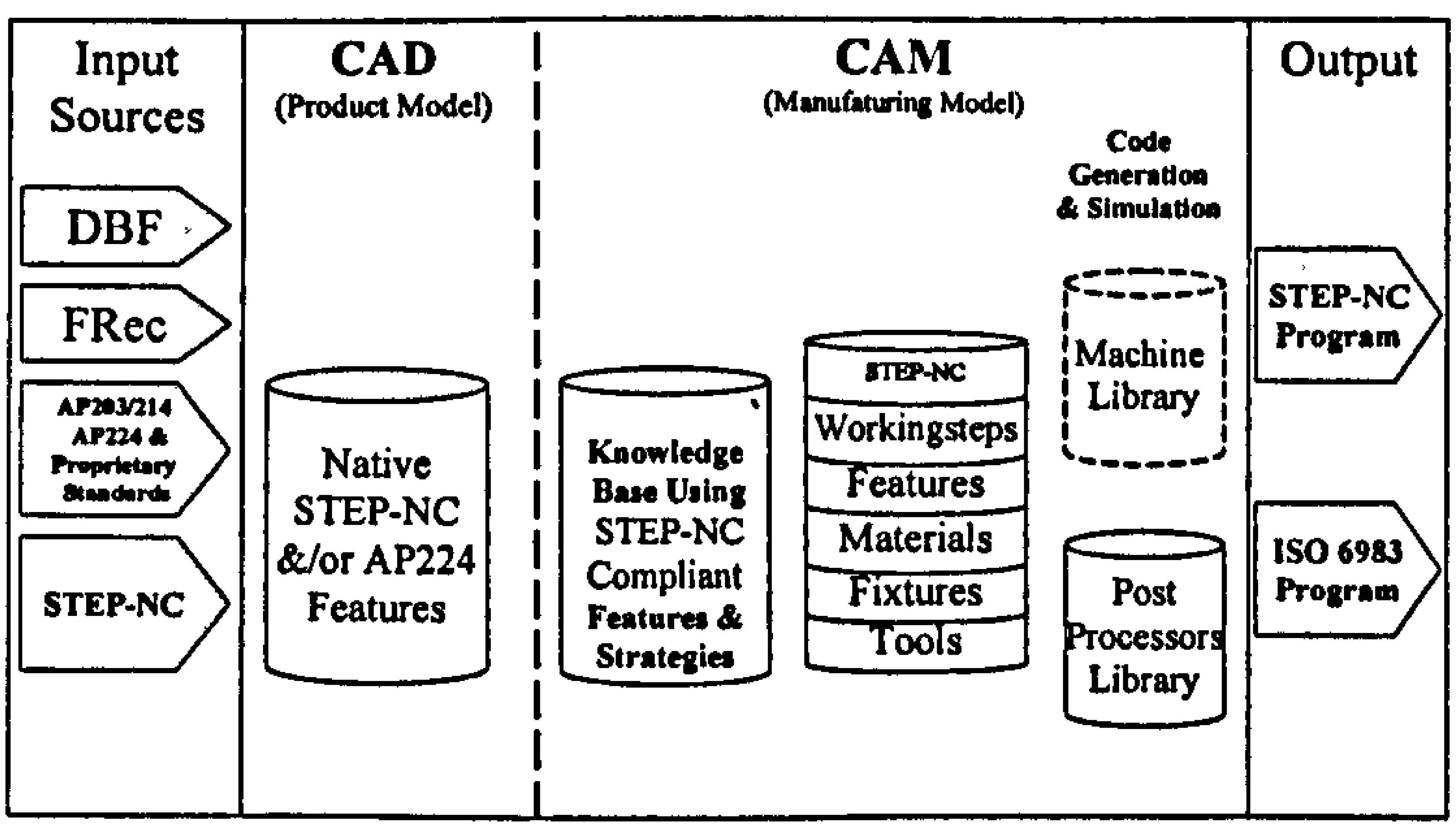


Figure 6.5 – CAD/CAM environment with kernel STEP compliant data structure

Chapter 7

Design and Specification of a STEP Compliant CAPP/CAM System

7.1 Introduction

This chapter outlines the research developments in the design of a STEP compliant CAD/CAPP/CAM environment which conforms to the third framework described in Chapter 6 section 6.3.3. The first part of the chapter is dedicated to the description of the information models designed to support the process planning activity. The second part describes a structured systematic methodology for the modelling of the process planning activity using a STEP compliant perspective.

It should be recognised that though the author has developed product and manufacturing models based on STEP-NC, these models have been extended with additional information to represent the resources namely the intelligent CNC machine tools.

7.2 Design of STEP Compliant CAPP/CAM

As stated before, this work is focused on the design of a CAPP/CAM environment that uses a STEP/STEP-NC compliant kernel, as a way to avoid translation between proprietary and standard formatted information. The research reported in this thesis provides a new approach for process planning of asymmetric rotational parts, which is achieved by the use of standards and the merging of the parts of STEP-NC for milling and turning parts.

In this research the design of a STEP compliant CAPP/CAM system for asymmetric rotational parts has been based on the following activities:

i) Modelling the Information Structure using STEP Standards and UML (see 7.3), and

ii) Using the IDEF0 Methodology to define the activities of a generic STEP compliant CAD/CAPP/CAM system (see 7.8)

To model the functionalities (activity model) of the prototype the author has utilised IDEF0, which is a well established methodology (see section 4.3). This part of the research is described in sections 7.8 to 7.8.4. In this research work the EXPRESS language has been used to represent the STEP entities (ISO10303-11 1994) together with the Unified Modelling Language (UML) methodology to describe the STEP Compliant Information Models. UML has been used, as it is an object oriented visual modelling language adopted as the standard by the Object Management Group (OMG) (Fowler and Scott 2000, Scott 2001). In addition UML provides the means to capture structures and behaviour of modelled objects (Scott 2001). As the structures defined in STEP are "object flavoured" the methodology is well fitted to this task.

The use of STEP compliant data structures in CAD/CAPP/CAM systems creates the basis for the integrated use of information. This approach is particularly suitable to integration of CAD/CAPP/CAM/CNC systems by the use of STEP compliant product and manufacture models. With the emerging ISO 14649 (STEP-NC) standard, the information generated in the CAD/CAPP/CAM process chain can flow seamlessly to the CNC controller. Thus, the integration from the CAD (design) to the CNC (machining) is provided using related ISO standards. Figure 7.1 shows the author's view of the ideal integrated model based on ISO standards relating to design and manufacture. The figure shows how product and manufacturing data is consistently captured at any level in the organisation, across the process chain. Thus, in the design of this new breed of CAx system, STEP and STEP-NC standards need to be consistent with at least one of the CAD/CAM frameworks described in Chapter 6.

The manufacturing model consists of information relating to resources in the form of AP 224, AP 240, AP 238 and ISO 14649. Within, the Manufacturing Model (MM) the process related data is in the form of ISO 14649 and AP224 which identifies the operations and related surface finish and tolerances. As can be seen in the product model the manufacturing/process data related to each specific part is similar to the data held within the manufacturing model. Here the product model holds information related to the part geometry and process plan in a format consistent with an ISO 14649 program. It should be recognised that at the time of this research AP 238 was available only for milling operations, with no schema for turning, thus the PM and MM in this research was designed without AP 238. During the writing up of this thesis a DIS version of AP 238 was released for public discussion in late October 2004, containing a version of the turning model.

This means that the designed system does not contain the geometric information consistent with AP 238(see section 4.6.5) and only contains the feature representation held in AP 224/ISO14649.

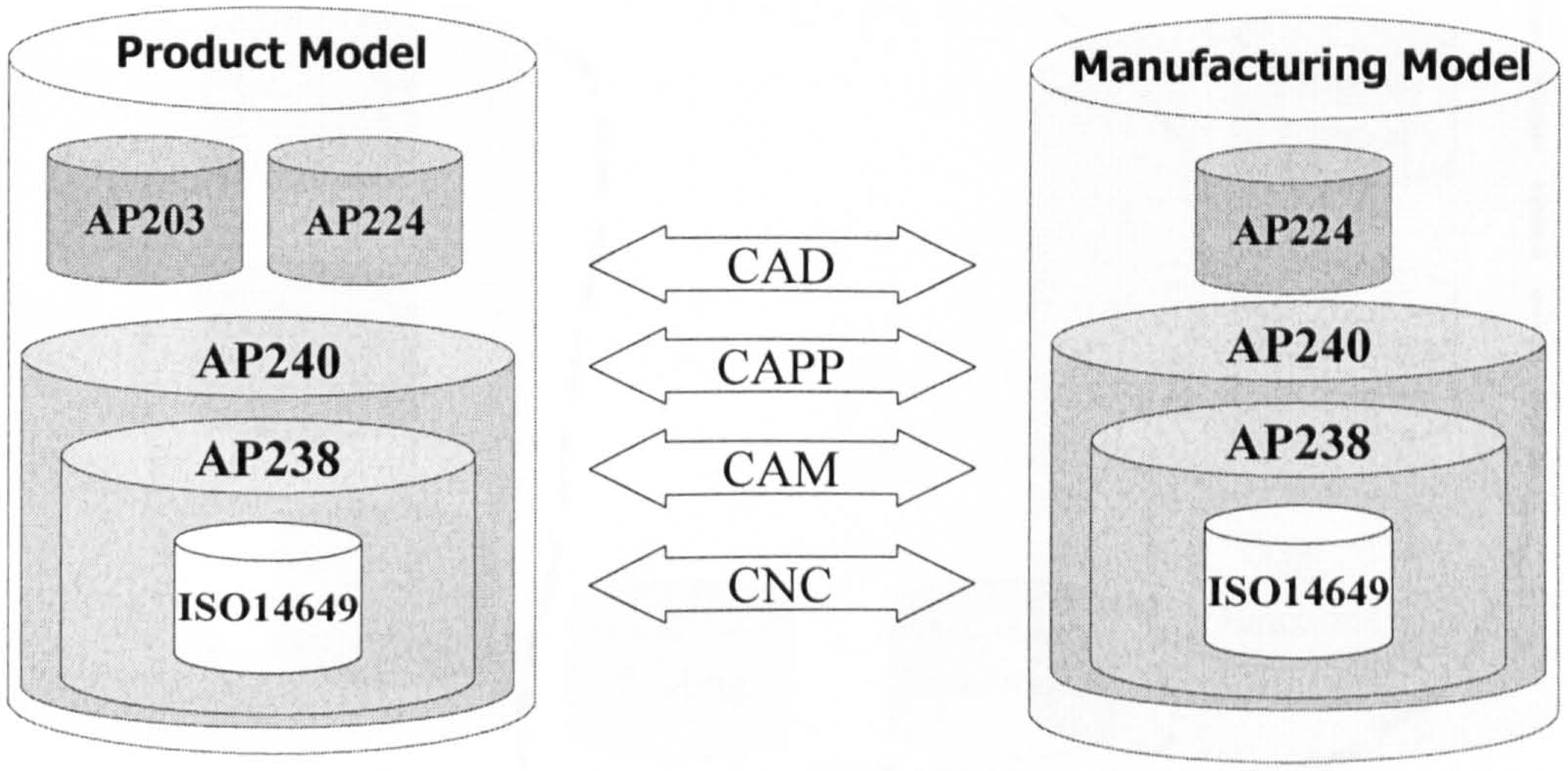


Figure 7.1 – STEP Compliant Information Model for integration of the chain from Design to Machining of a part.

7.3 Information Models to Support the STEP Compliant CAPP/CAM

In Chapter 3 the concepts of the Product and Manufacturing Model were reviewed and in Chapter 4 & 5 the standards related to manufacturing were described. In this research, these standards are used to define a novel approach to create an integrated information infrastructure to provide improved workflow across the production chain from the design to the manufacturing of a product.

Clearly the adoption of STEP/STEP-NC necessitates a requirement for a novel information model to support the tasks of CAPP/CAM. Thus, the use of the parts of STEP-NC for both milling and turning are required. Figure 7.2 depicts an overall view of the models to capture the information required for the process plan activity and generation of a STEP-NC program. The author has termed this information model as an extended STEP-NC model, as many of the parts are from ISO14649 and ISO10303 which are related to the STEP-NC standard.

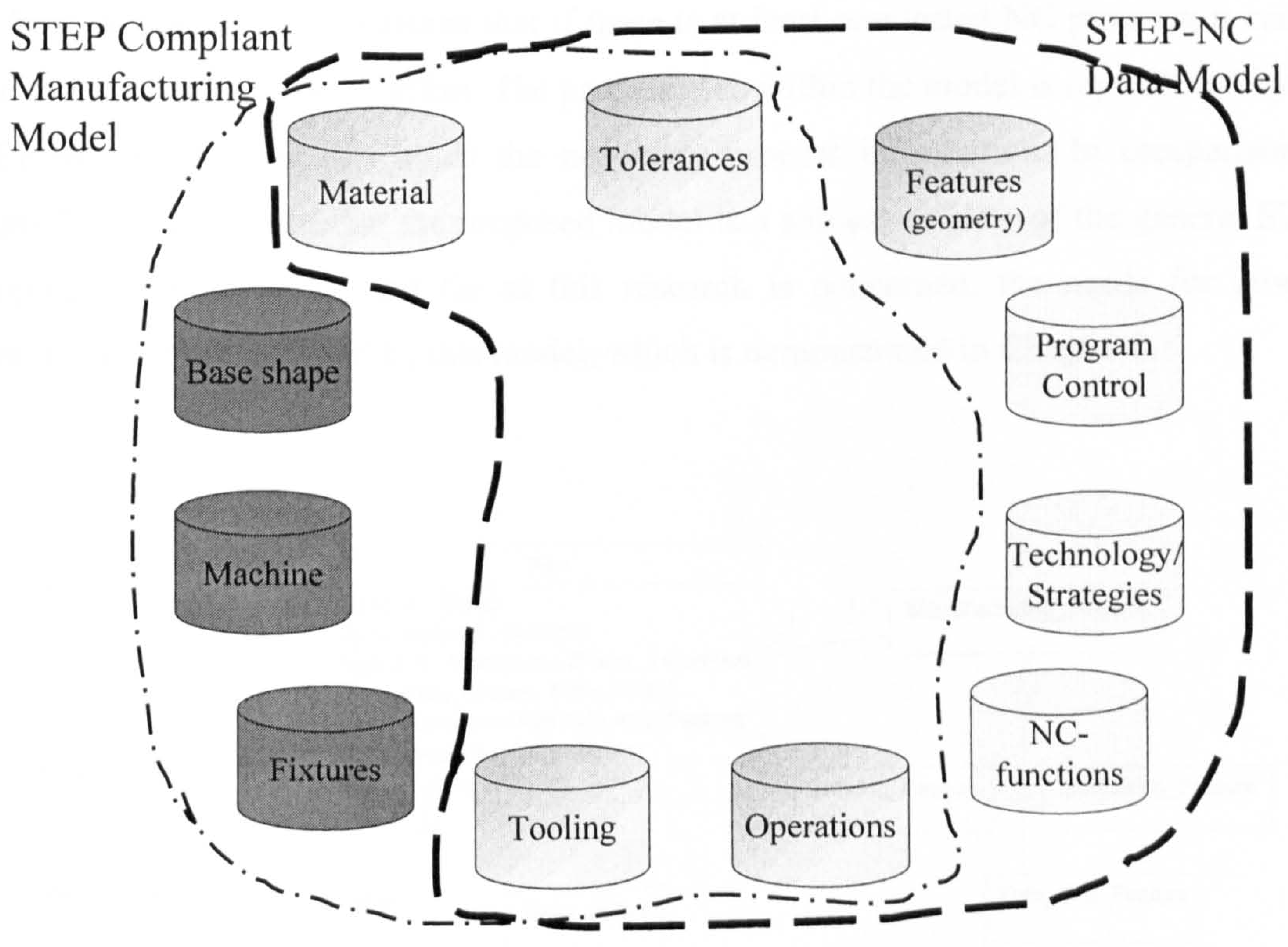


Figure 7.2 – Overall view of an extended STEP-NC model

7.4 STEP Compliant Product Model

In this work the Product Model (PM) is used to capture information related to the workpiece in terms of its features, material, tolerances, shape of the raw material and surface finish. It is based on the main class termed *Part* that holds all this information. It can be said that this is a feature based product model concerned in capturing information needed to generate a process plan. Each *Part* instance has information related to the set of features in the format of ISO 14649 with the additional surface finish parameters. As stated in Chapter 4, ISO 14649 features closely resemble AP224 features. In the initial versions of ISO 14649 the surface finish was part of the base classes for both milling and turning. It was however removed from the recent versions of the standard. To capture the information needed, the author added this attribute in the product model features to be in line with

AP224. The features in this model represent geometric shapes created by turning, milling, drilling or turn-mill operations. A *Base_shape* is the initial shape of the material before the machining of features as defined in AP 224, and can take the form of a cylinder, block, n-gon or B-Rep model. The classes *Process_plan* (using AP240) and *NC_Program* (using the ISO14649 standard) are used to store this kind of information after process planning has been performed. This ensures that if there is at least one tested NC program it can be used to avoid duplication of effort. The process plan within the model is represented by the STEP-NC program as this holds the necessary process information. In comparison to figure 7.1 it can be said that the proposed model is a sub-set or view of the general STEP compliant product model. As far as this research is concerned, the needs for process planning a part are satisfied by this model, which is demonstrated in Chapter 8.

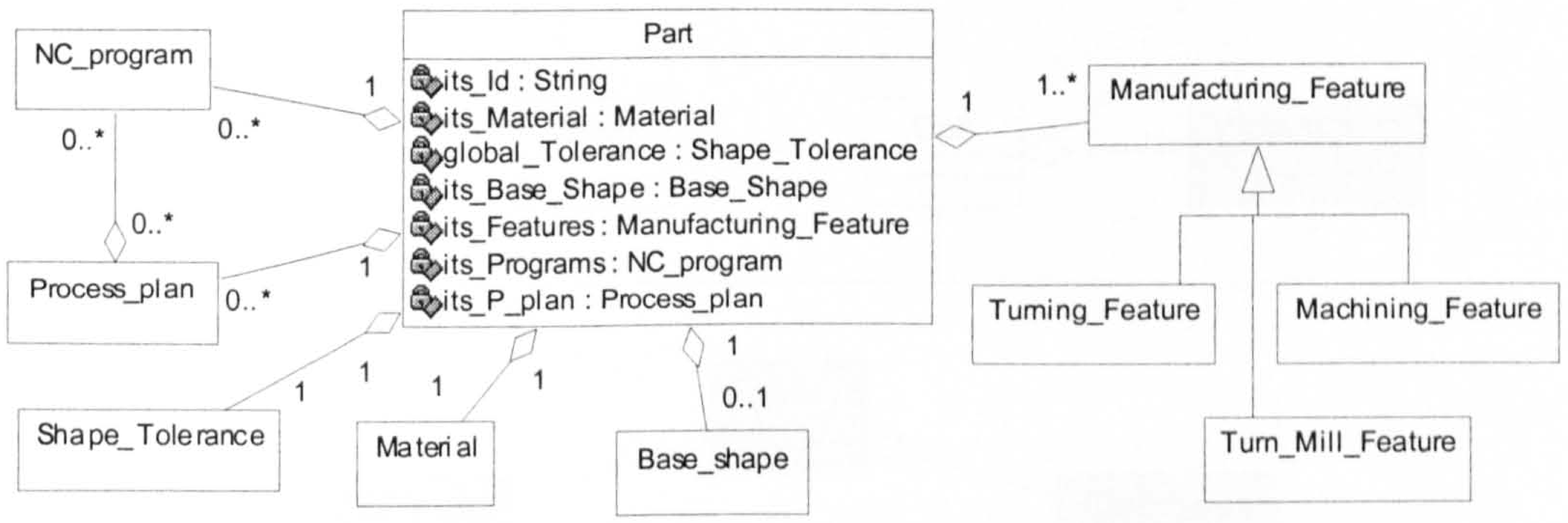


Figure 7.3 – Overall view of the STEP compliant Product Model

7.5 STEP Compliant Manufacturing Model

The Manufacturing Model (MM) is focused at the workstation level to support integrated applications in a STEP compliant integrated environment. It can, however, be easily extended to cell, shop and factory levels as in Molina's work (Molina 1995) and to the enterprise level as suggested by Zhao et al. (1999). In this case the MM entity called *Workstation_capability* is the facility described in the aforementioned work. The MM structure designed by Molina is illustrated in Figure 7.4(a) and uses the concepts of Facility, Resources, Processes and Strategies (Molina 1995; Zhao et al.1999). The author's research which focuses at the workstation level is illustrated in figure 7.4(b) where the major entities are: *Workstation_capability*, *Resources_capability*, and *Processes_ capability*. These are defined as:

Resources capability: The capability and limitations of the physical resources such as machines, tools, materials to produce goods.

Processes capability: The capability and limitations of a given process to perform an operation. The processes described in the present research are the material removal processes performed by machining operations such as turning and milling.

Workstation capability: The combination of a *Resources_capability* and *Processes_capabilities* in relation to a particular workstation that has machines, tools, fixtures, materials which perform the processes within the limits of their constraints.

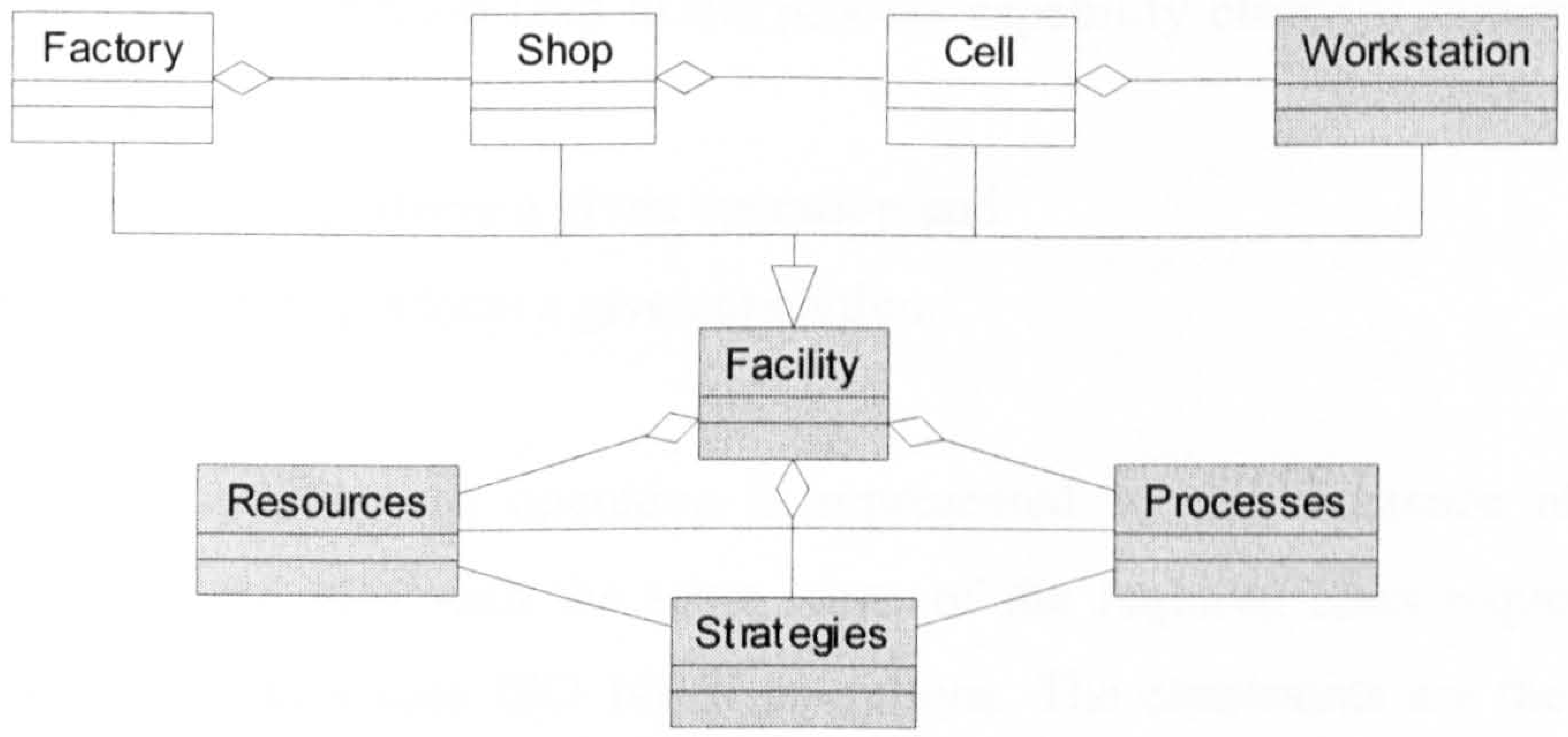


Figure 7.4.a – The top entities in the Manufacturing Model with a modified Molina's(1995) structure

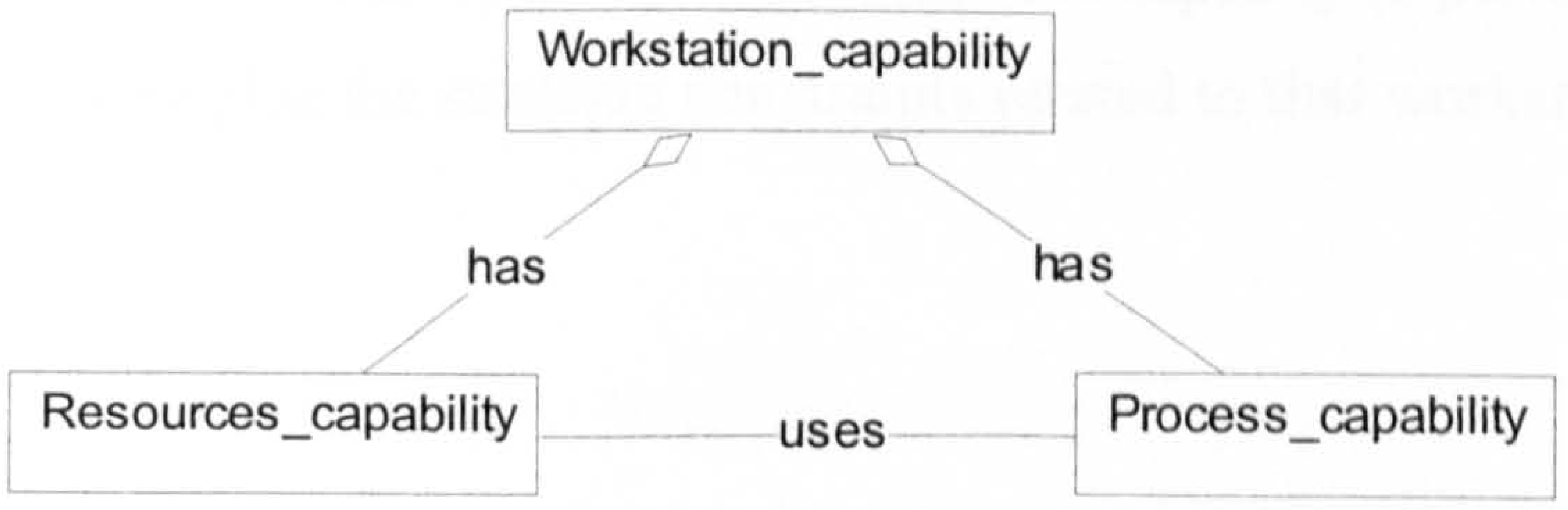


Figure 7.4.b – The top entities in the Manufacturing Model

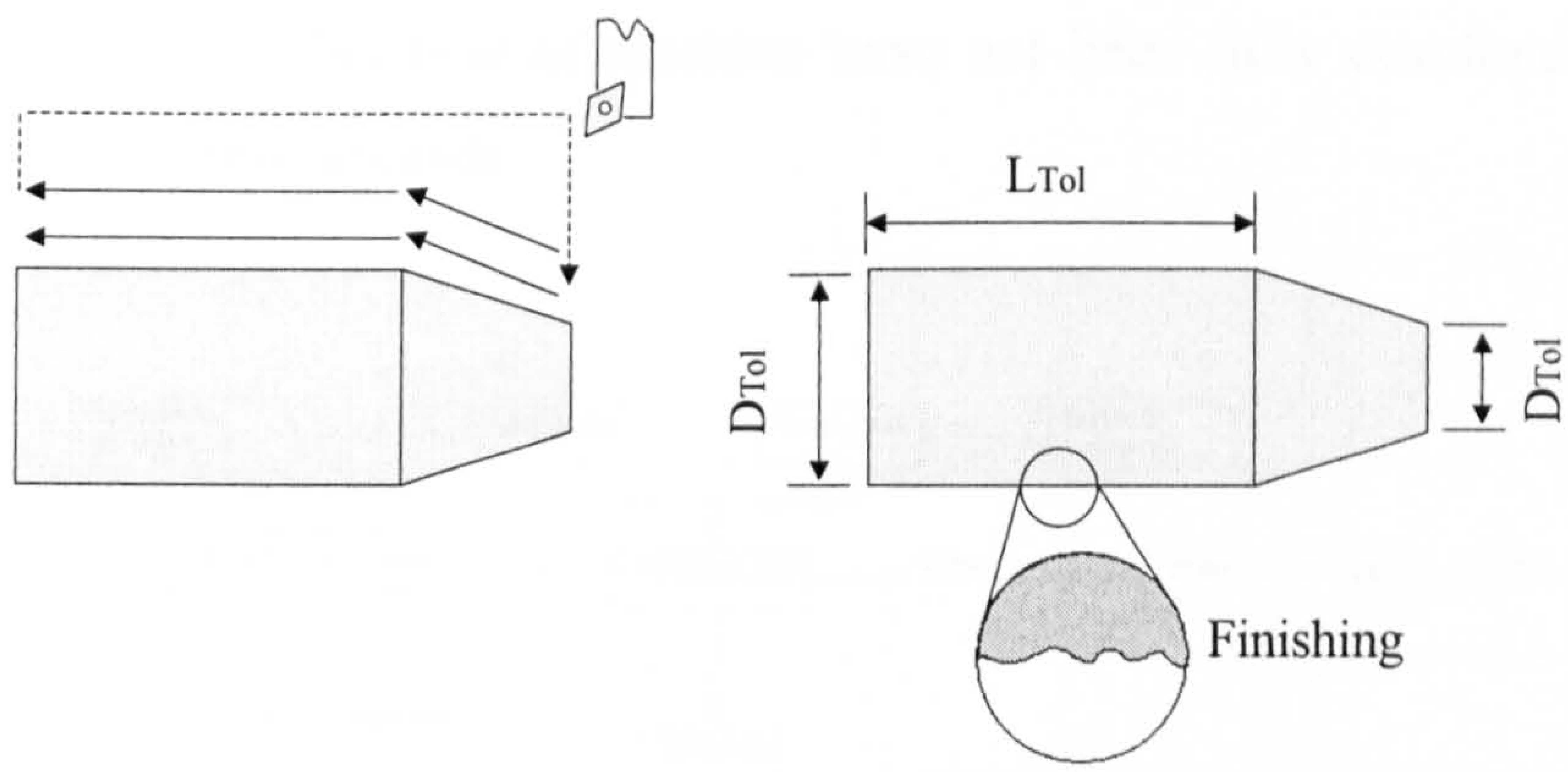
Figure 7.4 – The Manufacturing Model representations of Molina(1995) and Rosso

The author believes that the Facility class defined in Molina's work is redundant for process planning at the workstation level. It should be noted in the author's model the developed manufacturing entities comply as much as possible with one of the following standards which were described in chapters 4 and 5: ISO14649 (Parts 10, 11, 12, 111, 121), ISO 10303-224(AP224), and ISO 10303-240(AP240). The aim is to have a model that is neutral in concept and STEP compliant. Although other researches have followed the idea of the use of STEP compliant models as an integration tool (Liang et al 1999; You and Yeh 2002; Zha and Du 2002, Xu and He 2004), the use of this set of standards makes the author's research approach unique. Further more, it is applied in the context of turn-mill components, which is in its infancy for development as an ISO14649 standard.

It should be noted that in the author's MM the Strategies element defined by Molina is essentially the constraints imposed on the process. In the author's MM this was modelled using the ISO 14649 operation classes, with a different semantic meaning as defined in the standard. Thus the information held in the process capability class (of Figure 7.4(b)) are two fold namely:

- the capability to perform a given operation and
- the constraints to perform a given operation.

The capability to perform an operation is represented by the existence of the given operation class in the MM with the same name of the required class requested by the CAPP/CAM system as it uses ISO 14649 operations. The constraints are the parameters held within the operation class of the MM. Figure 7.5 depicts the semantic differences in the operation class in the STEP-NC data model and in the author's MM. The author's operation class in fact adds the constraints to the meaning of a STEP-NC class. Thus the MM has the operation class that semantically means: the capacity to perform the operation described in ISO 14649 plus the strategic constraints related to that workstation.



(a) STEP-NC meaning of contour operation (b) MM meaning of contour operation

Figure 7.5 -Semantics differences for Operation in STEP-NC data model and the author's Manufacturing Model

7.6 Modelling the Resource Capabilities

The major challenge in modelling the resources was to represent the required level of detail to describe the various resources related to the turn/mill process. As the granularity of the information in the model can add richness of detail, it can also bring the overhead of managing un-necessary information for the STEP-NC program generation. The author's intent was to define the resource information at a minimum level of detail, which enabled efficient generation of STEP-NC compliant programs. However, further information is needed to create an ISO6983 NC part program. This is because in G/M code programming low level and bespoke information is required to define machining data such as the position of a tool in the turret or magazine.

An overall view of the resources capability class is provided in figure 7.6. Where the resources are separated in two main classes namely:

- Raw_Material
- Manufacturing_machine_tool_resources

It should be noted that the *Resources_capabiliy* has been modelled specifically for use in a turning and turn-mill environment (lathe or turning centre). Therefore as shown in figure 7.6 these elements have been developed. In the case of the milling machine environment the entities needed for this type of machine have not been fully developed as they are outside the scope of this research.

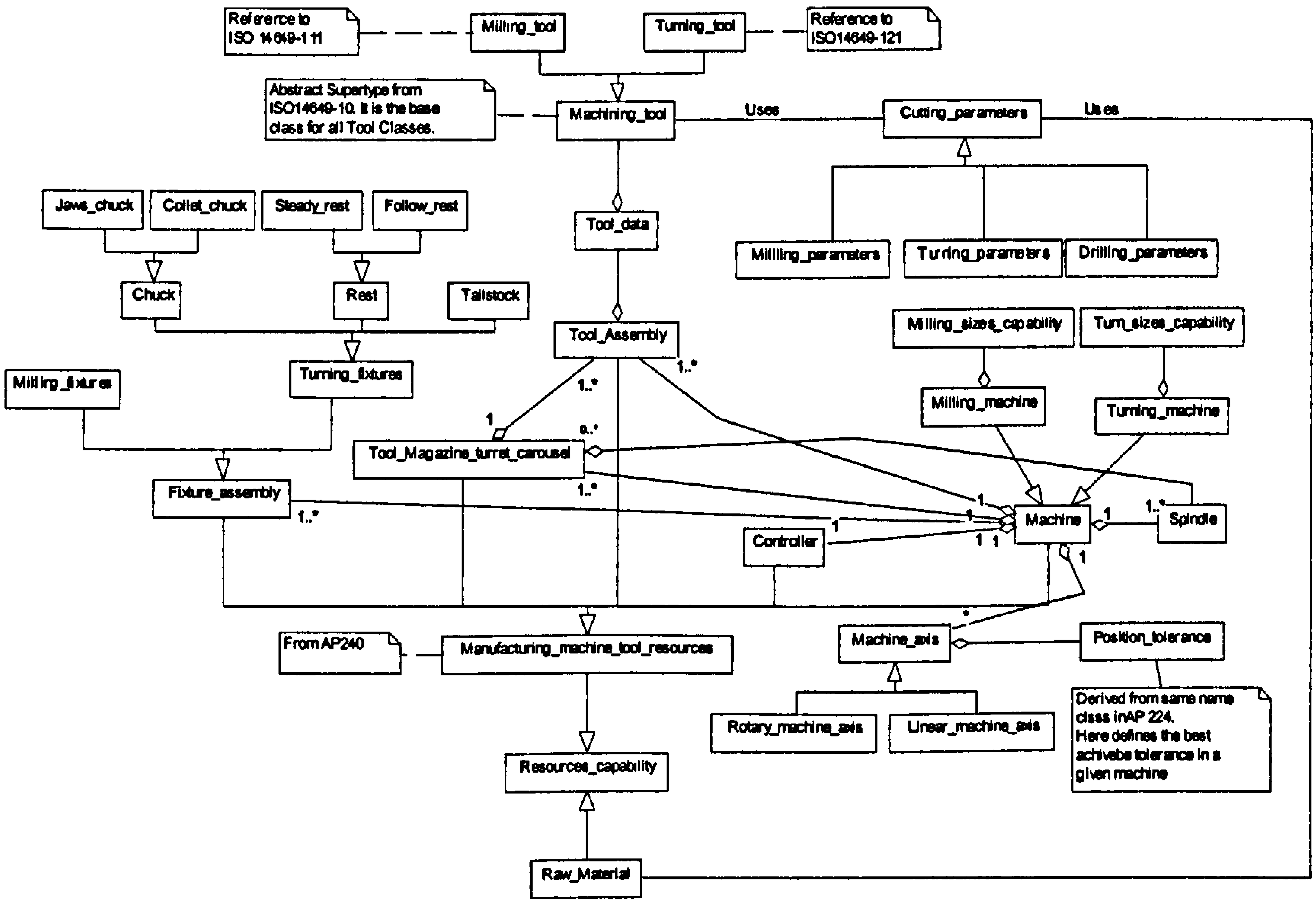


Figure 7.6 – Overall view of the *Resources_capability* class

7.6.1 The Raw Material Class

To characterise the raw material of a component it is necessary to know the national or international standard (e.g. ASTM, BS, ABNT) to which it belongs, its common name, the material type, the material property and its base shape. Through analysis of this information it is possible to determine the size of machine tool, the cutting tool material and associated cutting parameters.

Figure 7.7 depicts the *Raw_material* and *Property_parameter* classes of the MM. The first three parameters of the *Raw_material* class basically serve to identify the material. The type of material is used to help in selecting cutting parameters, using generic types such as steel, stainless steel, cast iron, titanium, non-metallic materials, aluminium and its alloys.

The material property can be the modulus of elasticity, hardness or any other property of importance.

The *Property_parameter* identifies the value and the type of properties. In general the most used property is the hardness as it is generally used to support the definition of cutting parameters. The *Base_shape* is the same ISO entity that was explained in the product model. With this information it is possible take decisions over the initial choice of machine tool as well as the required cutting tools

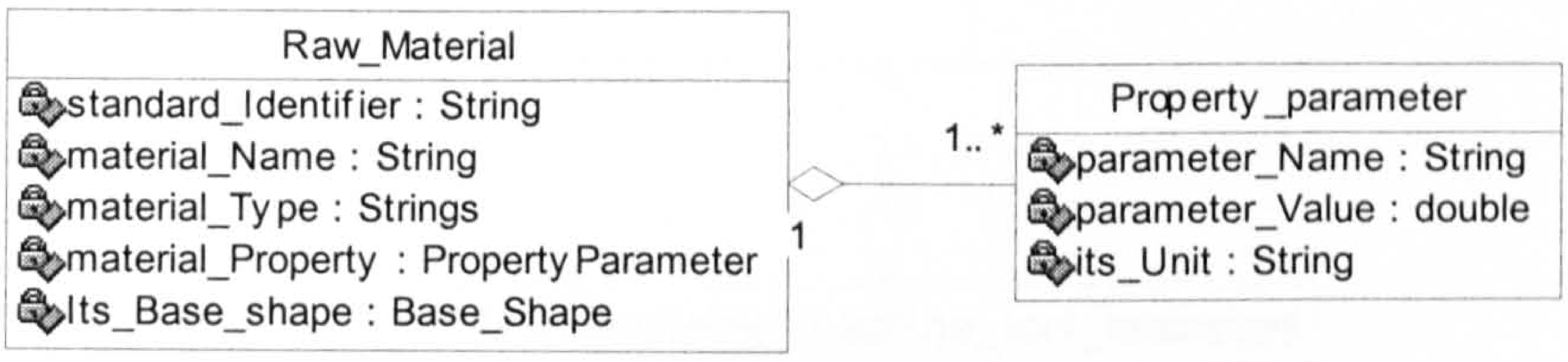


Figure 7.7 – The Classes *Raw_material* and *Property_parameter*

7.6.2 Manufacturing Machine Tool Resources Class

This is a base class to all machine related resources which include the machine itself and components, the tooling system(turrets/carousel), tools, fixtures and the controller. It is inherited from AP 240 (ISO10303-240 2003) and organises the resources in relation to the machine tool and identifies the major machine components together with other auxiliary resources such as tool and fixture assemblies. This is shown in Figure 7.8 which depicts the class *Manufacturing_machine_tool_resources* and its subclasses.

This model uses the following machine tool resources, which are described below:

- *Fixture_assembly*
- *Tool_assembly*
- *Tool_Magazine_turret_carousel*
- *Controller*
- *Machine*

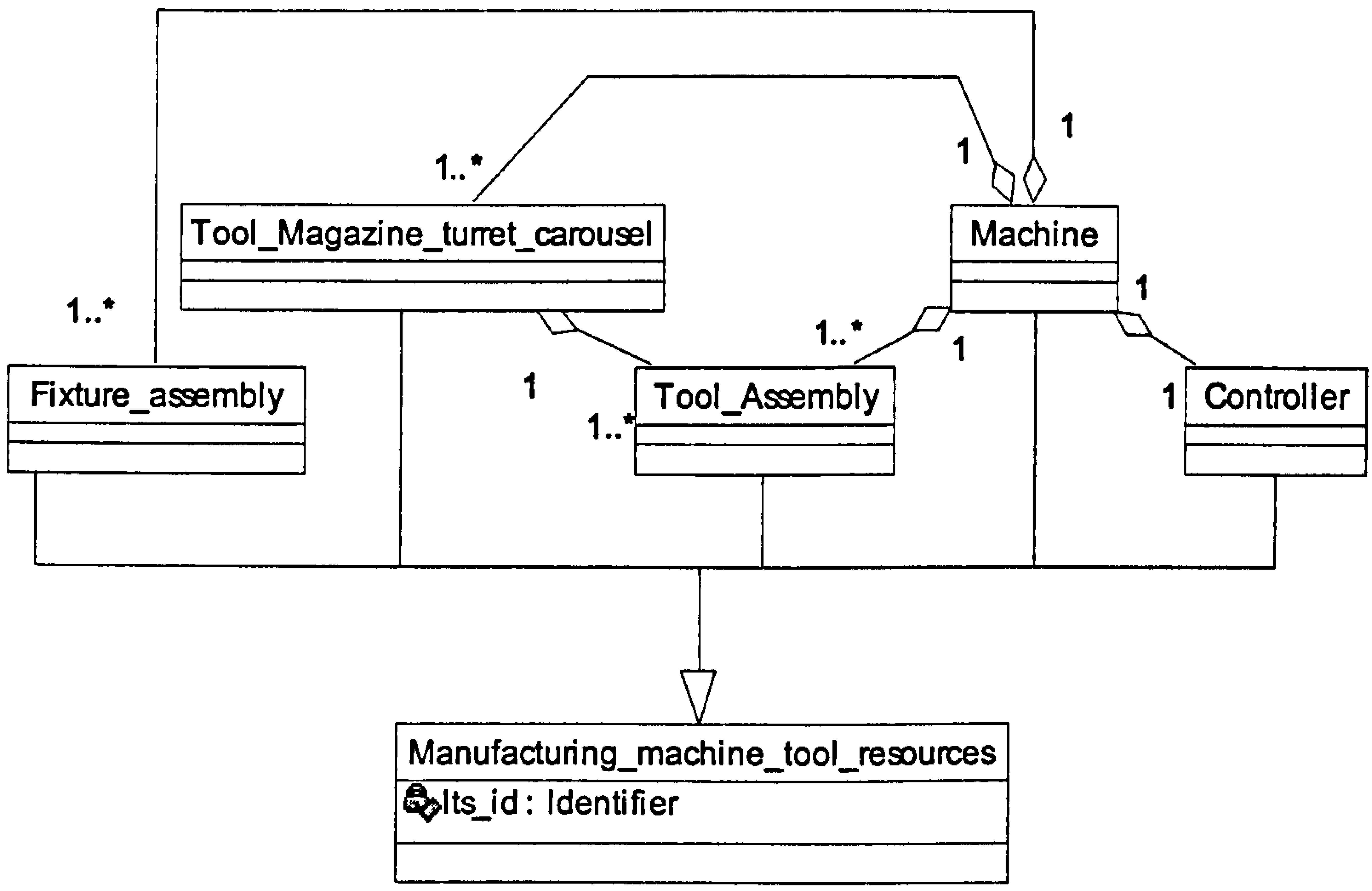


Figure 7.8 – The base class *Manufacturing_machine_tool_resources*

The *Manufacturing_machine_tool_resources* entity is defined in AP240 and it contains the definitions of tools, fixtures, and machine used to accomplish the fabrication of a part(ISO10303-240 2003). In this work it is used as the base class for all necessary resources related to a machine-tool including the machine itself.

i) Fixture Assembly Class

This class is divided in two sub-classes namely, *Turning_fixtures* and *Milling_fixtures*. The milling class appears for future development of a *Milling_machine* environment. The *Turning_fixtures* class was developed with the aim to support CAPP/CAM activities to generate STEP-NC programs. Therefore, the limited set of fixtures defined in the sub-classes of *Turning_fixtures* extends the STEP-NC model as the standard provides only the clamp positions (e.g. from chucks) and the information about the existence and the use of *Tailstock* and *Rests* (Steadies). Thus the model provides information such as the length of the Chucks (including the jaws) that can generate the clearance area in the STEP-NC program, the minimum and maximum diameter capacity of a rest which is used in process planning to define the suitability of the available fixture for the part, type of point(end) in the tailstock which can either be used to put a message to the STEP_NC program to change the live or dead end. Figure 7.9 depicts the *Fixture_assembly* class and its sub-classes. Thus, the information as most of those available in this part of the MM serve to support the user in taking decisions over the use of a given workstation. In addition, this part of the MM is used directly in the building of the STEP-NC program.

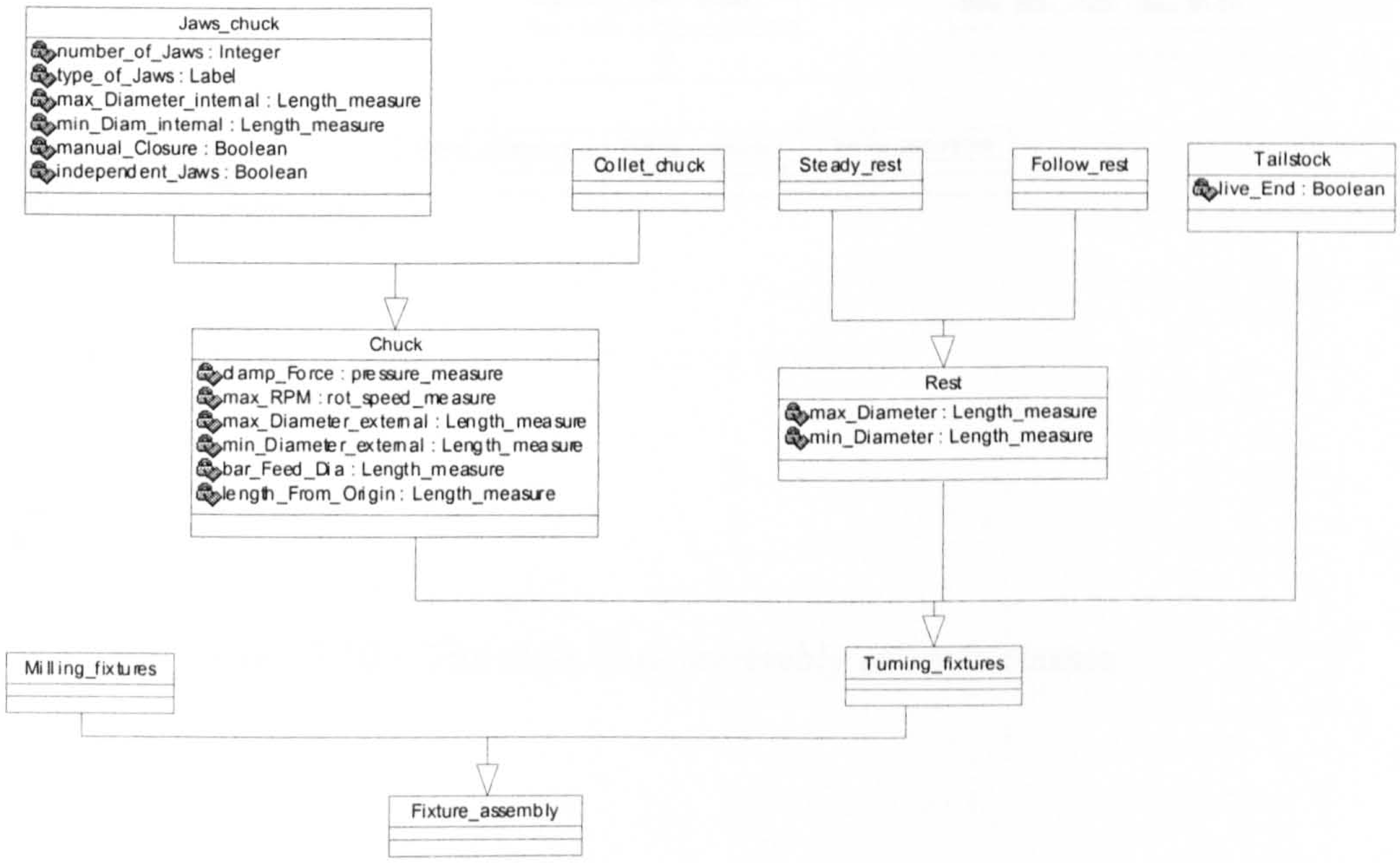


Figure 7.9 - The Fixture assembly class and its sub-classes

ii) Tool Assembly Class

The tool assembly class shown in figure 7.10, is modelled to represent the tool parameters necessary for a STEP-NC program. It has been defined with reference to AP 240 and the ISO 14649 parts 10, 11 and 12 which have definitions respectively for the abstract class *Machining_tool*, *Milling_ cutting_tool* and *Turning_cutting_tool*. They are aggregated to the *Tool_assembly* class through the *Tool_data* and use the class cutting parameters to define the cutting speed, feed and depth of cut. Thus the *Cutting_parameters* class uses the Raw material to compare the part material with the type of materials that can be cut by the tool material.

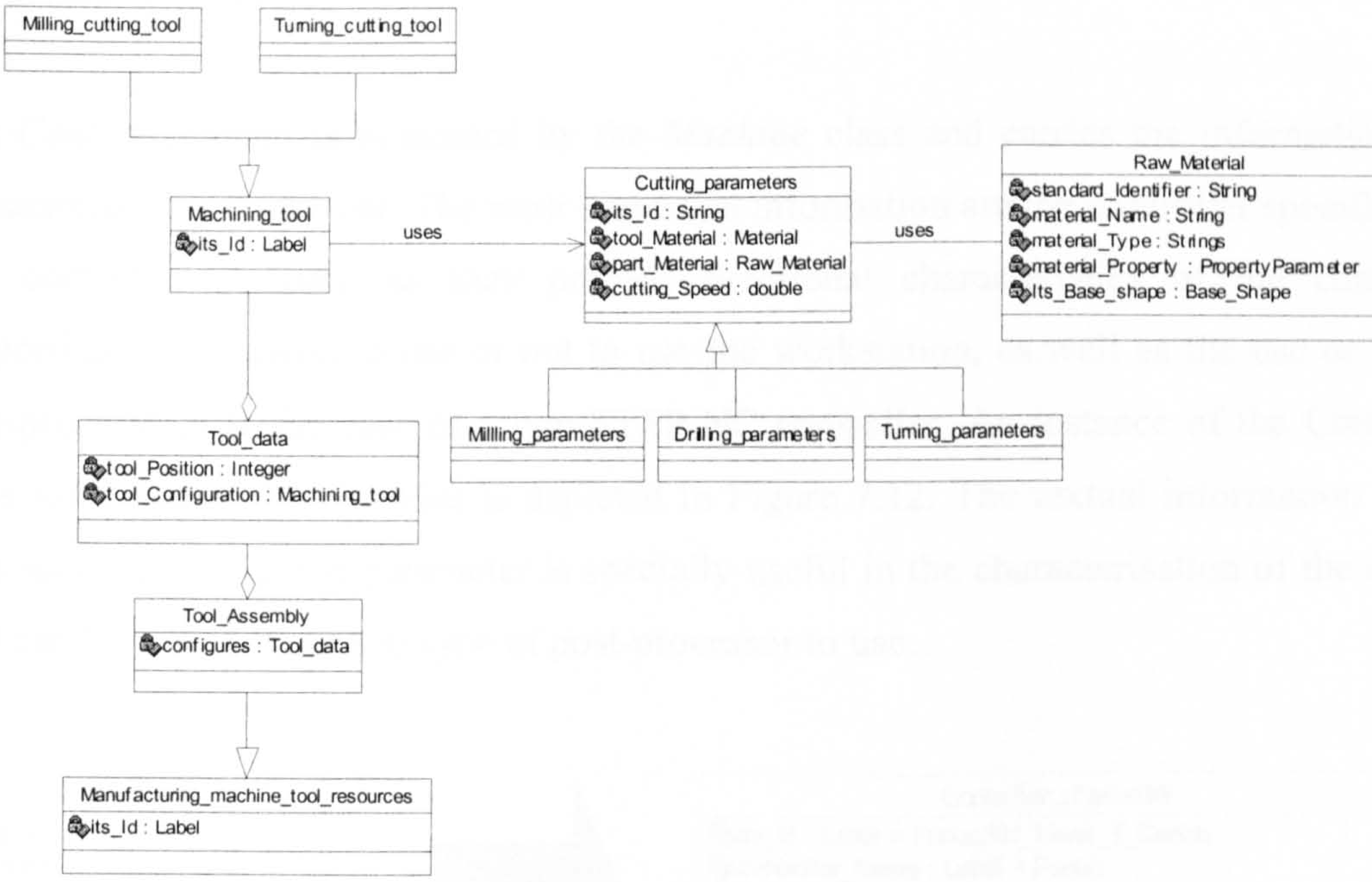


Figure 7.10 – The class *Tool_assembly* and sub classes

iii) Tool Magazine Turret Carousel Class

The *Tool_magazine_turret_carousel* holds the information such as number of tools, tool holder dimensions and the references to the classes Spindle and Tool assembly. Thus, it is a complex class that has two other classes used in the parameters. Then *its_Tool* parameter sets a list of tools in the format of Tools assemblies. The *Spindle* class provides information with regard to the drive motor of the live tools. Therefore, it may not exist in a workstation that uses only dead tools.

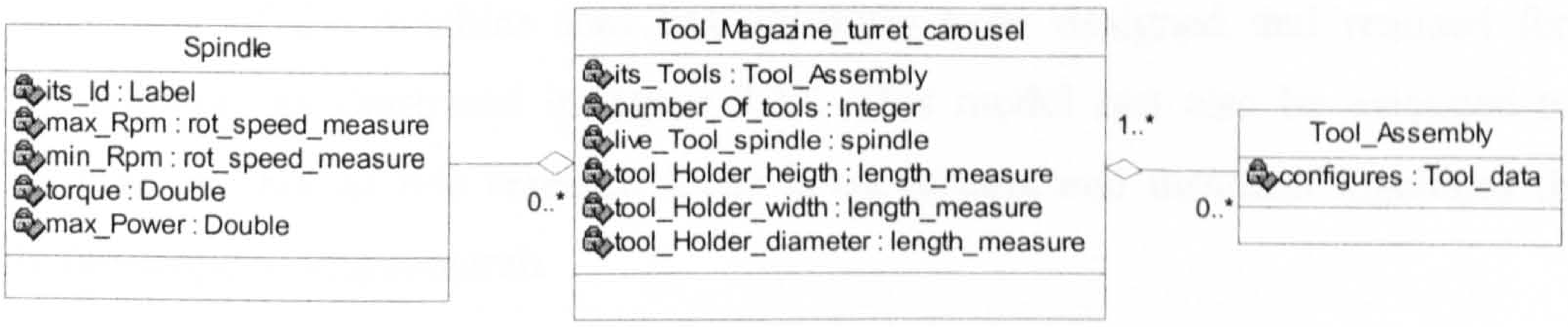


Figure 7.11 – The class *Tool_magazine_turret_carousel* and the aggregated classes

iv) Controller Class

The *Controller* class is possessed by the *Machine* class and carries the information that characterises the controller. The most important information are the controller specification and controller standard as they provide functional characteristics of the controller supporting the decision to use or not to use the workstation, as well as the use or not of post-processing, in the case of a non-STEP-NC controller. An instance of the Controller class for a Fanuc30i controller is depicted in Figure 7.12. The textual information in the *Controller_specification* parameter is specially useful in the characterisation of the device as it can hold details such as type of post-processor to use.

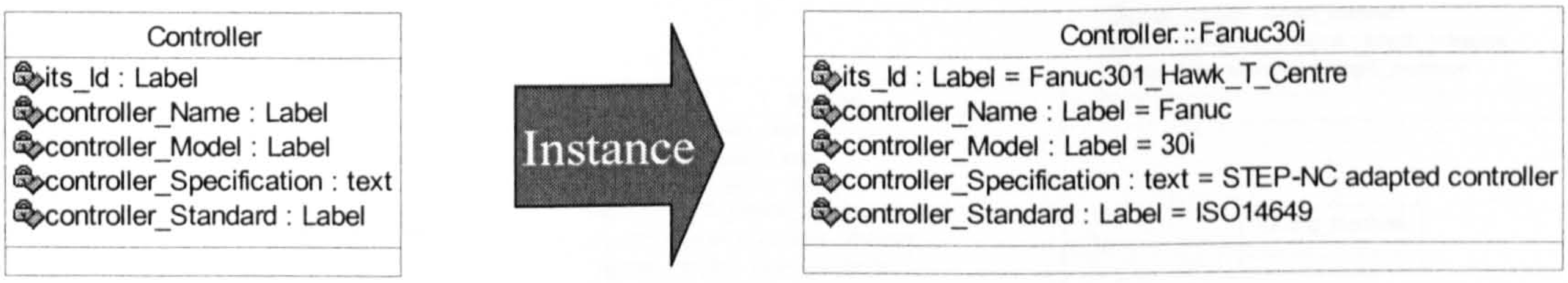


Figure 7.12 – The controller class and an instance representing a STEP-NC adapted controller

v) Machine Class

The machine class possesses the other sub-classes of the *Manufacturing_machine_tool resources.* In modelling this class the aggregation relationship was used in the UML model. The relationships between the Machine and other resource classes of Controller, Spindle *Tool_magazine_turret_carousel* and *Tools* are depicted in Figure 7.13.

The modelling of the machine tool has currently been designed and realised for the *Turning_machine* as illustrated in figure 7.13. This model can also be extended to the *Milling_machine* but as this research focus is on turning and turn/mill machines this is outside the scope of this research.

The author's MM was conceived to use turning centres and lathes to work with both symmetric and asymmetric rotational parts. However, the model can be extended to represent milling machines with four and five axes which have the capability to undertake secondary turning operations in milling centres for which the author's preferred name is machining centre. Therefore, in the definition of the two sub-classes of machine the author created the *Turning_machine* class and the *Milling_machine* class. The first class describes machines, which have turning as the main process but can have milling as a secondary process. The second class describes machines, which the principal process is milling but can perform turning as a secondary operation. It should be recognised that the model can be extended through the addition of further processes such as laser hardening and grinding.

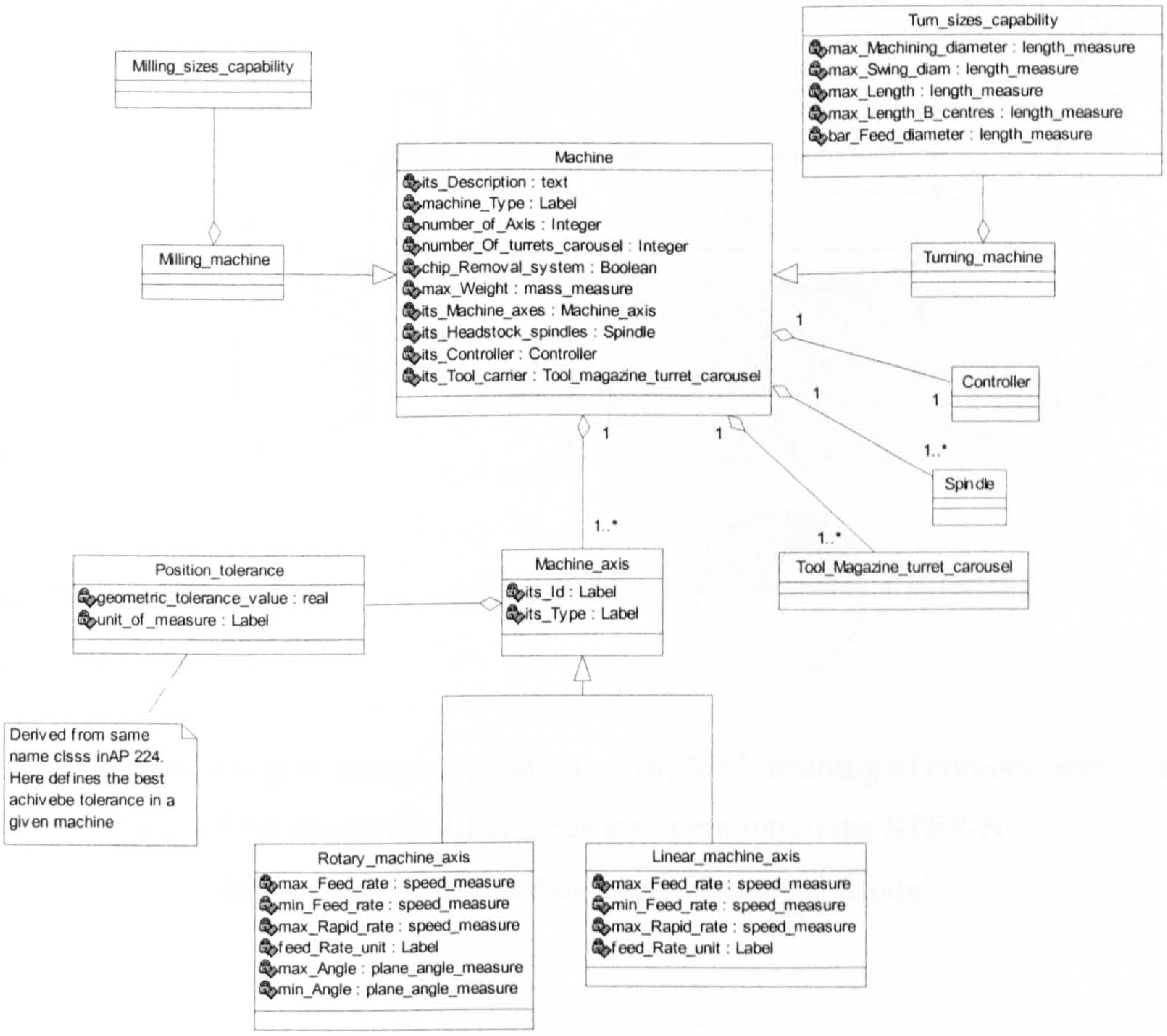
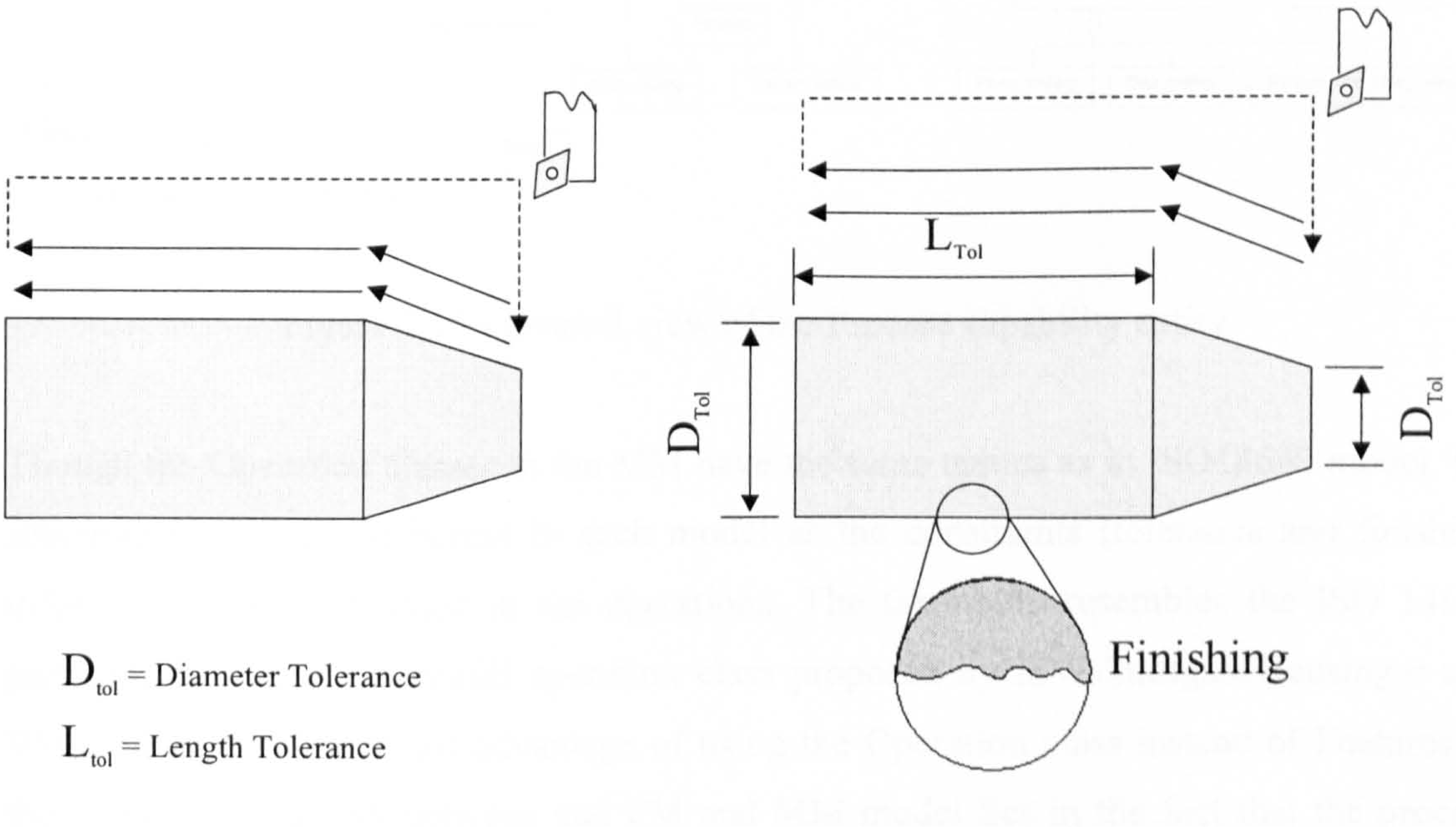


Figure 7.13 – The Machine class and its relations with other classes in the manufacturing model

7.7 Modelling the Process Capabilities

As previously outlined in section 7.5 the process capability definition in the author's MM represents both the capability and the constraints to perform a given operation. This is illustrated in figure 7.14 through an example of a contouring operation. Figure 7.15 depicts the structure of the process capability entity.



(a) STEP-NC meaning of contour operation (b) MM meaning of contour operation

Figure 7.14 -Semantic differences for operation in the STEP-NC data model and the author's Manufacturing Model

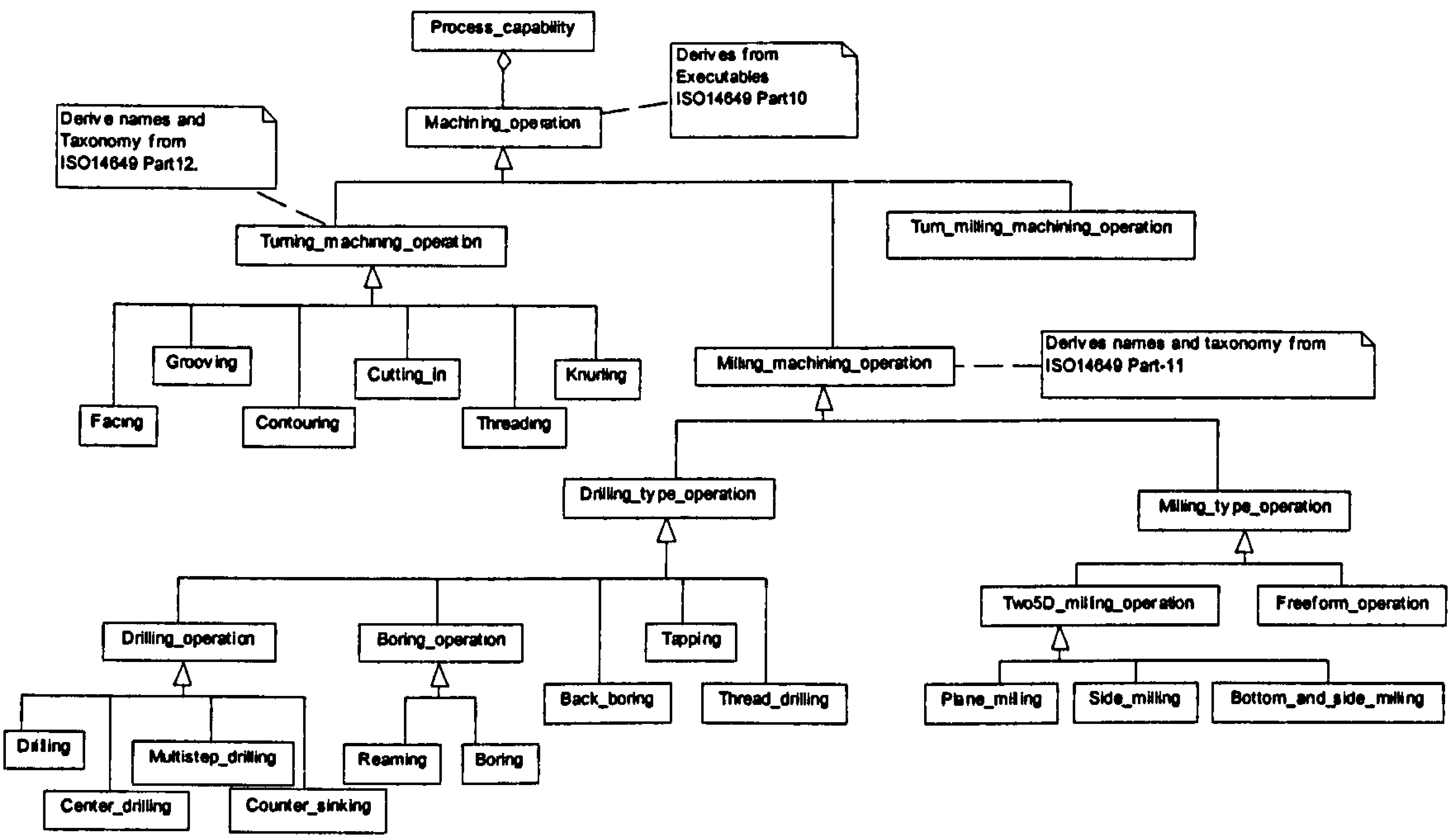


Figure 7.15 - Overall view of the Process capability entity

Though the Operation classes in the MM have the same names as in ISO14649 model, the semantic meaning is different in each model as the constraints (tolerance and finishing information) are embedded in the operations. The taxonomy resembles the ISO 14649 parts 11, 12 and the turn/mill operation class proposed by ISW-Stuttgart(Heusinger and Wosnick 2003). The major advantage of using the Operation class instead of Features as the manufacturing link between and PM and MM model lies in the fact that the process planning of a component typically happens at an operation level where one or more features are machined with the same tool with roughing and finishing cuts, rather than feature by feature. This is consistent with the definition of the operation as defined in ISO14649, which can be used on one or more features. Once an operation has been selected by the CAPP/CAM system to process a feature or group of features (from the PM), the model will enable information to be accessed, which identifies the feature through the process capability and constraints for the workstation. Thus mapping the operation with its process capabilities onto an appropriate resource.

7.7.1 Turning Machining Operation Class

The Turning Machining Operation class uses the taxonomy described in ISO 14649-12 (turning model) and is divided in the sub-classes *Facing, Grooving, Contouring, Cutting_in, Threading* and *Knurling*. In figure 7.16 the details of the sub-class Grooving are described.

It should be noted that the explicit information are not related to the operation itself but to the limitations regarding the use of the given operation in a given machine. In addition, the implicit information is the type of tool motion in relation to the features. This is in line with the use in ISO 14649.

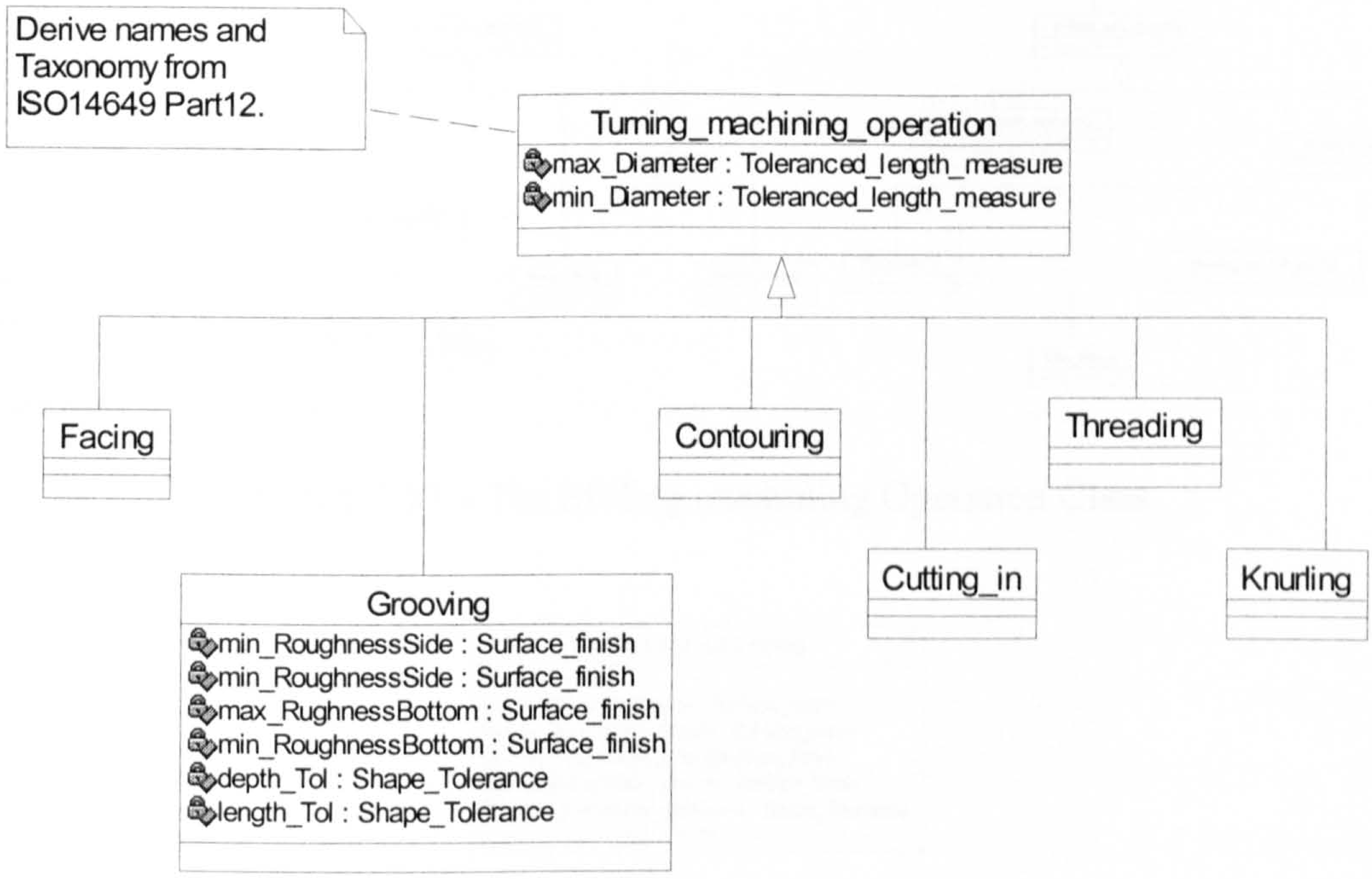


Figure 7.16 – The turning machining operation class with the details of the constraints held in the Grooving operation

7.7.2 Milling Machining Operation Class

The Machining Operation class uses the taxonomy described in ISO 14649-11 and is the base class for Milling and Drilling operations. The ISO 14649 taxonomy classifies milling and drilling operations as sub-classes of the Milling Machining Operation therefore naming them as Milling type operation and Drilling type operation respectively. Section 5.7 provides a more detailed discussion on the milling machining operation in ISO 14649-10. Figure 7.17 describes the structure of the *Milling_machine_operation* in the manufacturing model and Figure 7.18 shows the detail of the representation of the *Bottom_and_side_milling* sub-class.

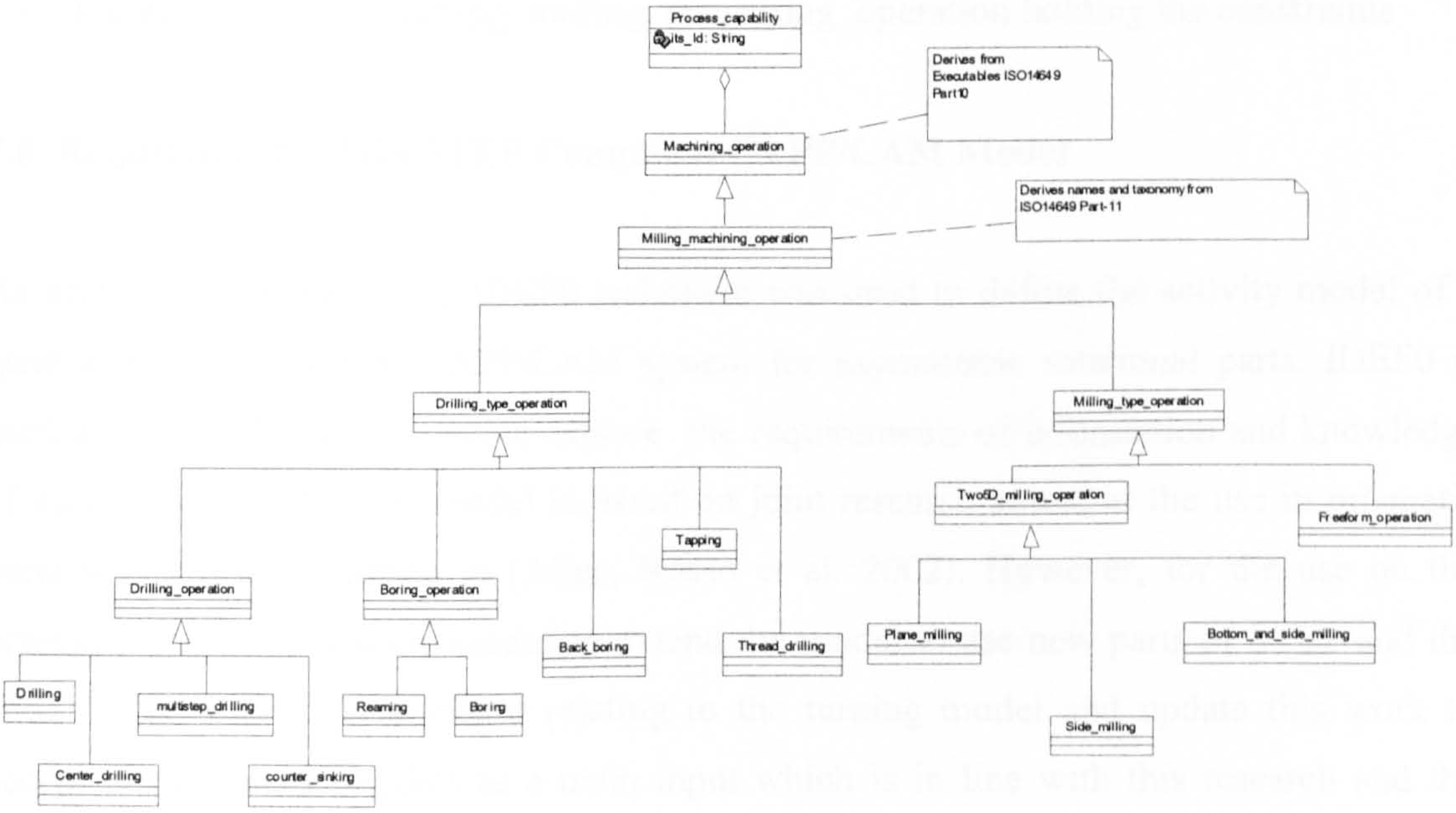


Figure 7.17 – The Milling machining Operation Class

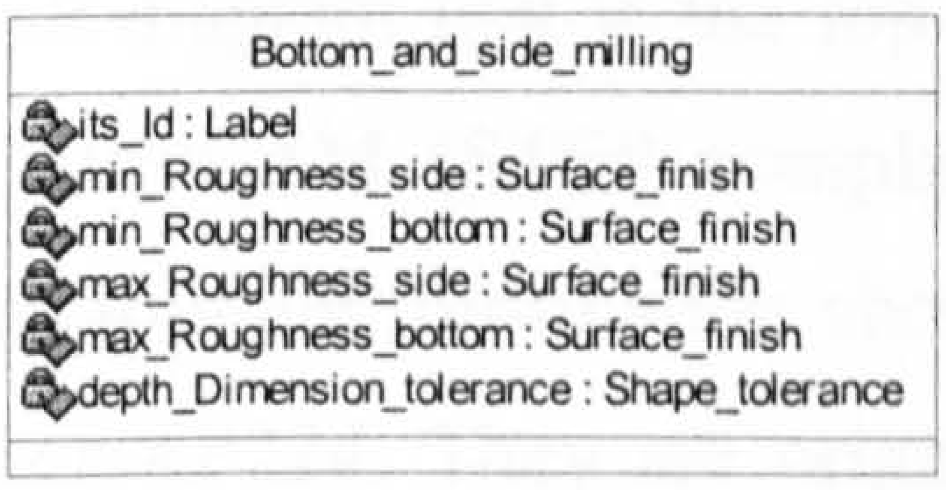


Figure 7.18 – The Bottom and side milling operation a subclass of milling machine operation

7.7.3 Turn Milling Machining Operation Class

The *Turn_milling_machining_operation* is at present the least developed part of the STEP-NC as it is not yet included in any part of ISO 14649 standard. In the MM it holds the surface roughness attributes for the machining of the two types of turn-mill features. Figure 7.19 depicts the *Turn_milling_machining_operation* in the manufacturing model.

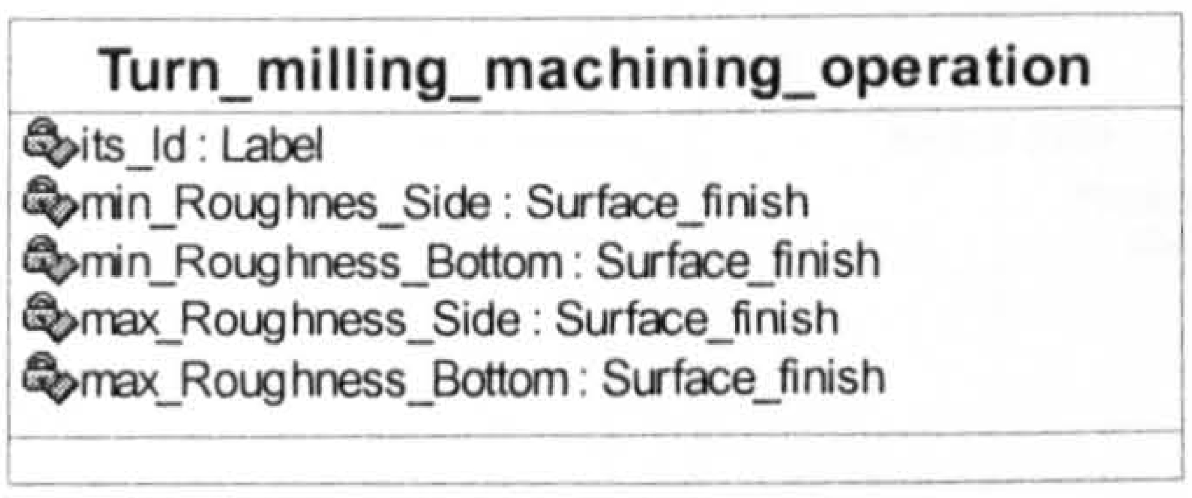


Figure 7.19 – The Turning_milling_machining_operation holding the constraints

7.8 Requirements of the STEP Compliant CAPP/CAM Model

As part of this research, the IDEF0 technique was used to define the activity model of a generic STEP compliant CAPP/CAM system for asymmetric rotational parts. IDEF0 is used as it provides the means to capture the requirements of information and knowledge of each functionality. The model is based on joint research aimed at the use in prismatic parts which was published in (Allen, Rosso et al. 2002). However, for the use on the present research the author needed to extend the model to use new parts of STEP and the parts of the ISO14649 standard relating to the turning model and update this work to accept feature based models as a main input which is in line with this research and the frameworks identified.

Figure 7.20 illustrates the overall diagram that is the top node (A0) of the part program generator termed STEP-TM CAPP/CAM (STEP compliant Turn/Mill CAPP/CAM). It outlines the two possible formats to input information about the workpiece model namely files in format AP214/203 and/or AP224. They are originated from a CAD system that should provide information about the geometry, material, surface, finish and tolerances. The outputs from the system are two fold:

i) An ISO 14649 physical file which would be used in a STEP-Compliant intelligent controller
ii) An ISO 6983 program which can be used in conventional controllers

The reason for the second output is that the author believes that there will be a long period in which both technologies will be used as the industries would not invest to replace the installed controllers immediately. Thus, any new CAPP/CAM system using STEP-NC technology would provide both outputs to comply with the needs of the transition period.

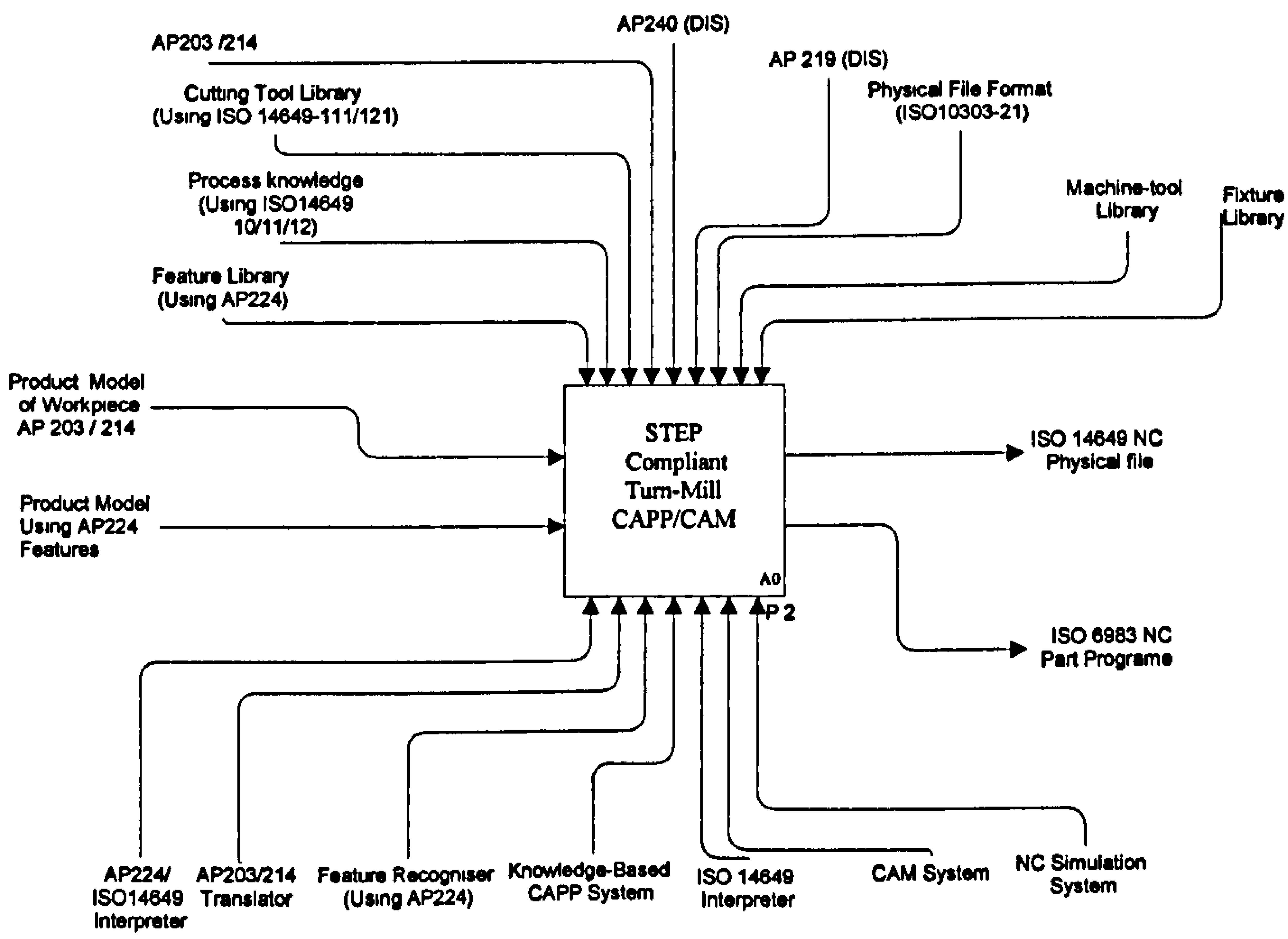


Figure 7.20 - The overall IDEF0 Diagram for the STEP Compliant CAPP/CAM for asymmetric rotational parts.

7.8.1 STEP Compliant Turn-Mill CAPP/CAM

The first sub-level design of the STEP Compliant Turn-Mill CAPP/CAM is divided into three activities which perform the tasks necessary to interpret the information in the product model to create a process plan and part program. The tasks are:

i) The extract feature activity
ii) The generation of STEP compliant NC process plan, and
iii) The generation of a controller specific part program.

The feature extractor is used to generate information such as type of feature and feature parameters to the process plan generator. The STEP compliant process plan is created using the information provided by the features extractor and using the information in the processes parameters libraries to output an ISO 14649 physical file. Figure 7.21 describes this sub level of activities. The related research on going in other institutions foresees that the next generation intelligent machine tool controllers will perform all calculations to create the tool trajectory(Weck and Wolf 2003; Suh et al. 2003; Suh et al. 2002; Weyrich et al 2000). The generation of a controller specific part program activity provides the functionality to create ISO 6983 programs to be used in conventional controllers.

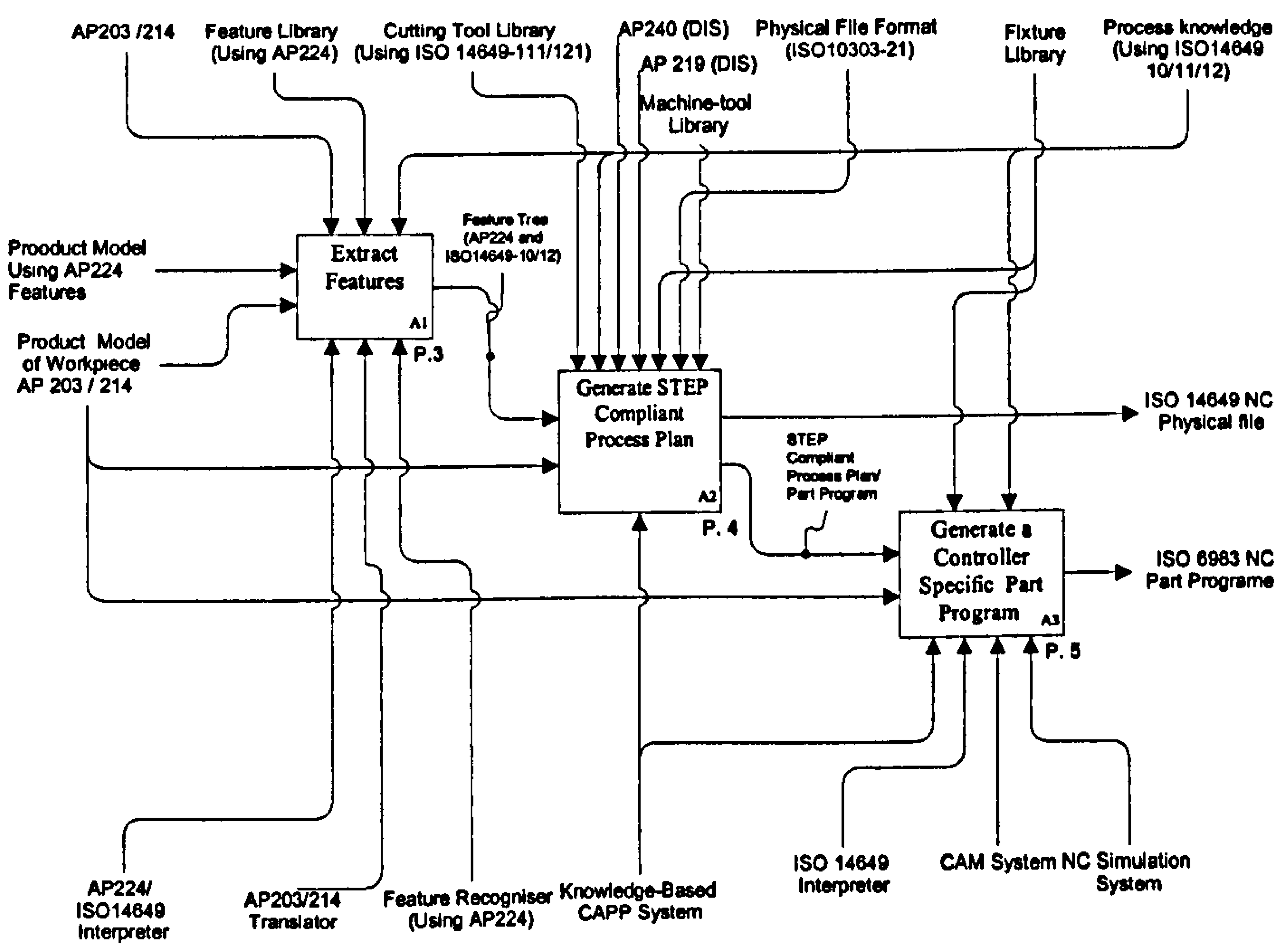


Figure 7.21 - IDEF0 representation of the first sub level of STEP Compliant Turn-Mill CAPP/CAM

7.8.2 The Feature Identification

This activity complies with the four sub-activities to create a readable set of STEP features to be used by the process plan generator. Figure 7.22 describes the extract feature sub-level with the sub-activities:

i) Analyse STEP 203/214 file,
ii) Identify features,
iii) Extract feature parameters, and
iv) Generate the STEP compliant data structure

In the event of an input from only AP203 the feature information is lost. Thus, to perform the task of process planning this information needs to be generated again via features recognition where there is identification of features and extraction of their parameters. The output is a set of AP224 features that is then written in a readable format of objects to be the input of the process planner. Some research works which generate AP224 features have been identified (Fu et al. 2003; Han et al 2001) and these would form the basis for future developments.

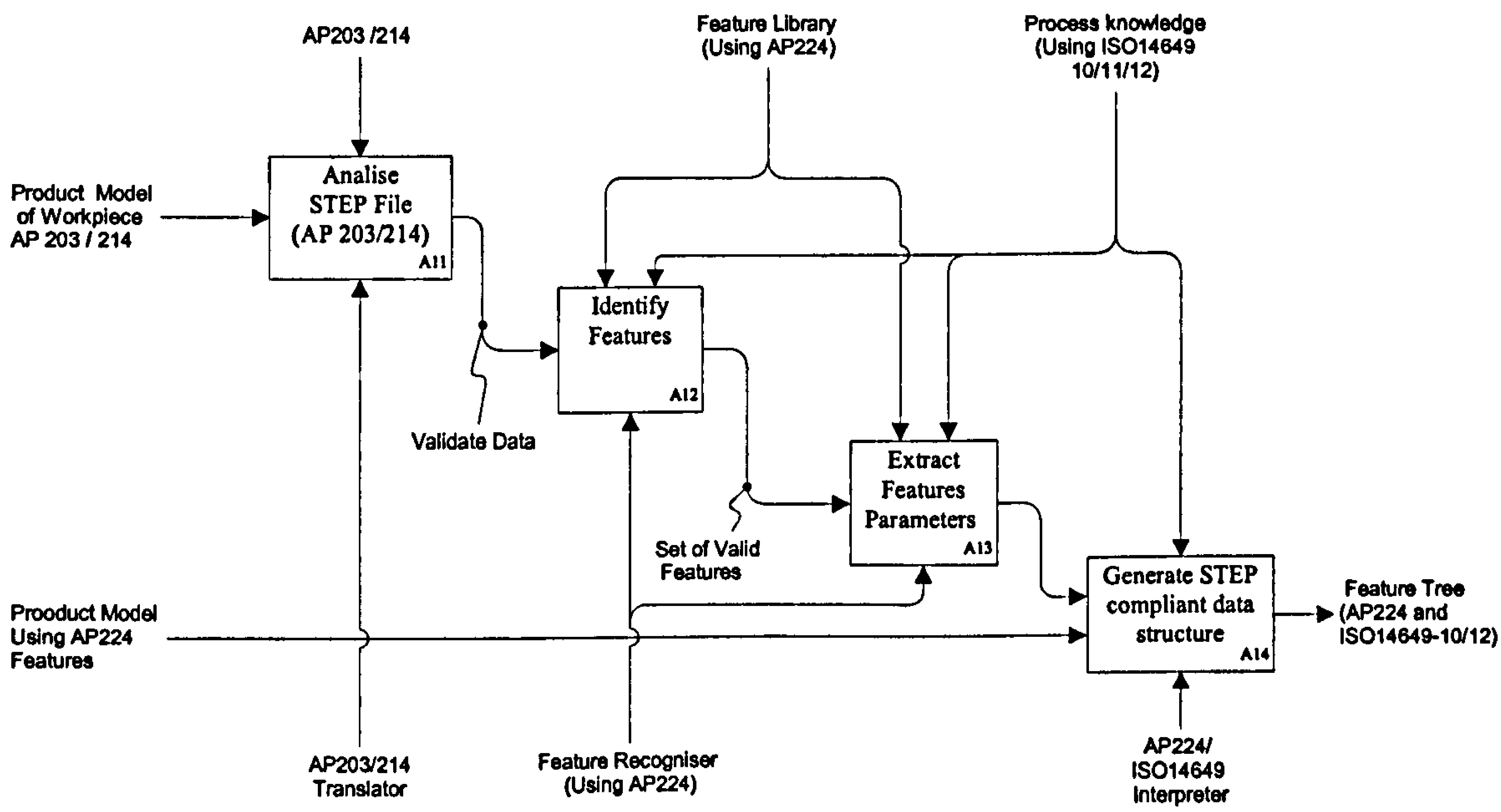


Figure 7.22– The IDEF0 diagram for the extract features activity

Feature recognition is out of the scope of this research but needs to be in the model to comply with the needs of the industry. In the third level framework showed in Figure 6.5 Section 6.3.3 there are two ways to obtain an AP224 model, by importing the model, or by an integrated STEP compliant CAD system. From the CAPP/CAM point of view they are the same as the input is an AP 224 file. If there is a workpiece model based on AP224 features those can be input straight to the last sub-activity where the features objects are mounted to be input in the process plan generator.

7.8.3 Generate STEP Compliant Process Plan Activity

This is the main activity in the system as it performs the task of generating the STEP-NC physical file, this contains much of the information related to a process plan. It can be mapped as the central part of the framework depicted in figure 6.5 Section 6.3.3 where the process planning occurs. Figure 7.23 describes the IDEF0 representation of this sub-level which is divided into seven sub-activities namely:

i) Define Fixturing and Set-up
ii) Process Selection & Operation Definition
iii) Machine Tool Selection
iv) Cutting Tool Selection
v) Cutting Parameters Selection
vi) Create Workingsteps and Workplan
vii) Optimise Workingsteps ad Workplans

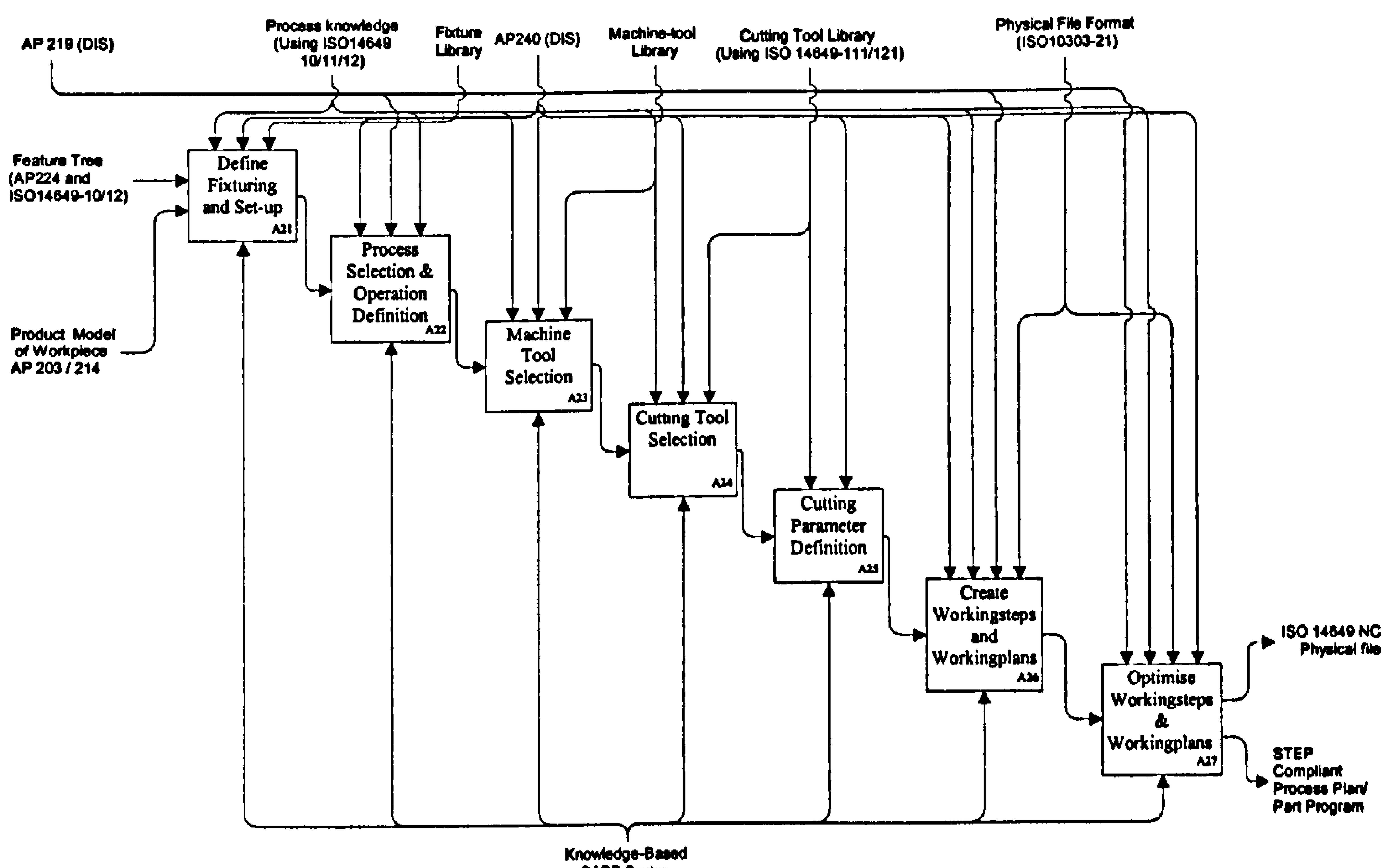


Figure 7.23 - The Generate STEP compliant Process Plan Activity

At this point the feature objects based on ISO14649 were created and are able to hold the information about their operations generated during the process plan. The selection of process uses the knowledge based on the ISO 14649 parts 11 and 12 where the type of operations available to each manufacturing feature is selected and allocated to the feature. The machine tool selection is used only when a machine specific program has been generated and needs to guarantee that the machine holds the capability to perform it. If so, the machine's information based on the model defined in this research is used. However, most of the STEP-NC programs should not be tied to a specific machine. Then, the tools are selected based on a library that uses ISO114649 part 111(tools for milling) and part 121(tools for turning). The cutting parameters are selected from the tool/material information and added to the operation object. The definition of fixturing and set-up is two fold: the definition identifies if one or more set-ups are needed, and what type of work holding devices are used such as rests, chucks and tailstock together with the location of these on the workpiece. The workingsteps are composed by the features and operation information such as rough on *Outer_diameter*. The workplan defines the sequence and use of the workingsteps therefore the task of sequencing operations/features is performed through sequencing the workingsteps.

7.8.4 Code Generation

The sub-level activity described in Figure 7.24 is to provide an output program using ISO6983 standard. It uses two inputs where the main input is the ISO14649 process plan / part program that is the output of the process plan activity. The second input is the workpiece model in format of AP203/214 which provides the ability to be able to generate the tool path trajectories avoiding collisions and also to be the user in the simulation task. The sub level is divided in four sub-activities as follows:

i) Generate data structure
ii) Generate tool trajectory
iii) Check collision
iv) Generate NC Code

The first activity generates a data structure based on the output of the process plan to be used in a CAM system. In the case of the use of the third STEP-NC framework described in Section 6.3.3, this sub level represents a STEP compliant CAM system which can generate the tool trajectories and check them for collisions. The result is post processed in to a specific ISO6983 format. The task of generating specific code and simulation is not in the scope of this work and has been described to reference the complete framework proposed. Simulation using STEP-NC code has been developed in other research (Suh et al. 2002; Suh et al. 2003) so far for milling machining.

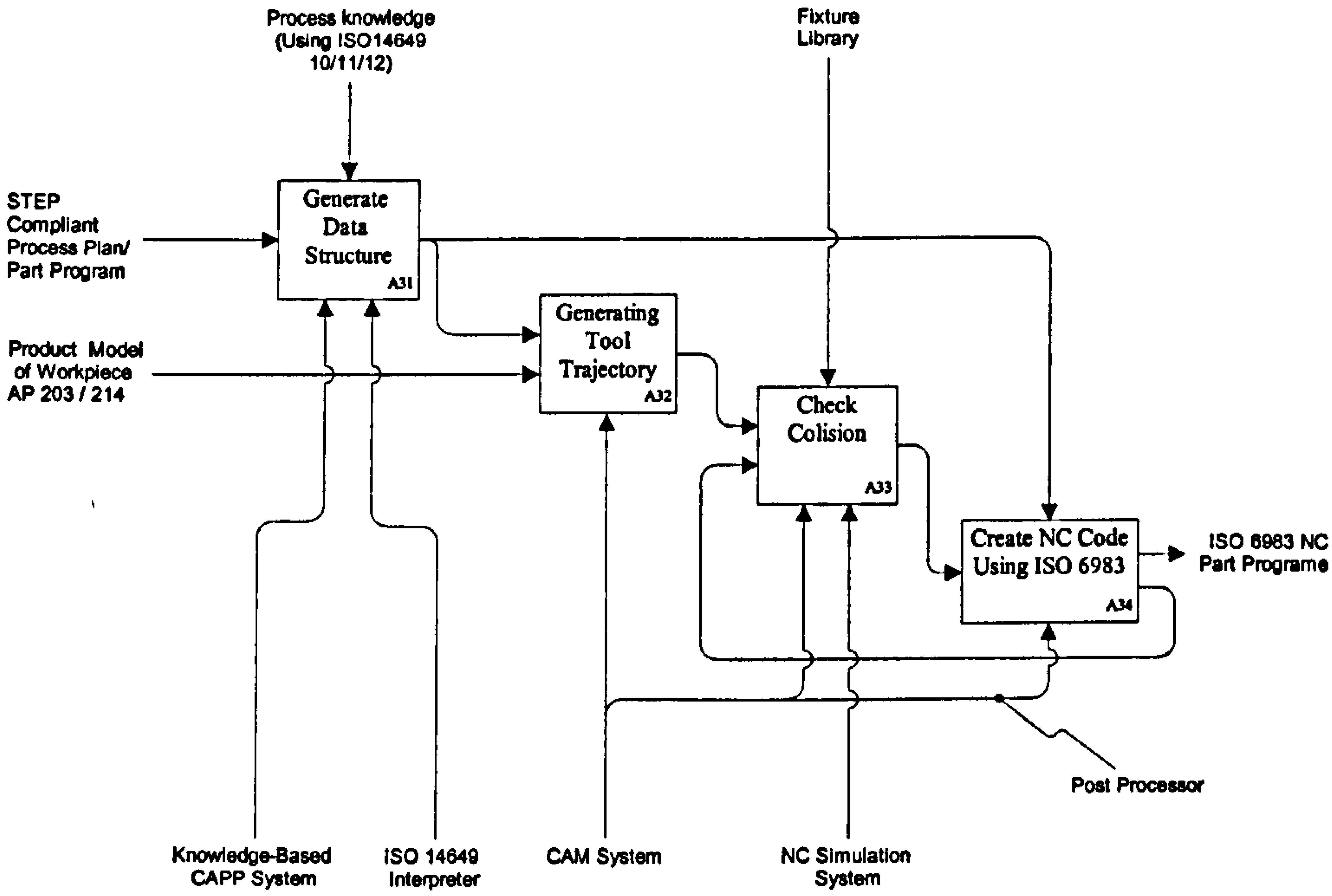


Figure 7.24 – The Generate Code specific activity that generates ISO 6983 part program from a STEP compliant CAPP/CAM system

Chapter 8

Realisation of a STEP Compliant Turn/Mill CAD/CAPP/CAM Environment

8.1 Introduction

This chapter describes and illustrates the STEP compliant Turn/Mill system (termed STEP TM-CAPP system) designed by the author. The information models described in Chapter 7 support the proposed system together with the information models defined in the ISO14649 standard used to create the NC programs. In this chapter the realisation of the use of both the information models and the supported proposed system is described by the modelling of a turn/mill workstation and through the use of user interfaces dialogs that depict the information held in the models. The case study component was developed to prove the concept for using the milling and turning parts of ISO14649 to provide a turn-mill CAD/CAPP/CAM environment. In addition the component also verifies the STEP compliant manufacturing model in supporting the process planning activity.

8.2 Operational Structure of the CAx System

In Chapter 7 the activities of the proposed CAx system were described using the IDEF0 methodology. The structure of the proposed system is comprised of a series of stages which perform the process planning activities as described in Chapter 7. Figure 8.1 depicts the general operational structure of the proposed system where, the manufacturing model and the product model work together with the STEP compliant TM-CAPP system.

This operational structure of the STEP-TM CAPP system has been designed based on the IDEF0 generic STEP-NC model representation outlined in figure 7.20. It consists of 4 major components:

- Product Information Retrieval Module
- Process Planning Module
- Program Generation Module(STEP-NC and G/M codes), and supporting
- Product and Manufacturing Models

The first module retrieves product information from the product model. The process planning module represents the recognised steps in process planning systems as shown in figure 8.1 and the final module the program generation creates NC part programs from the information generated by the process planning module.

The following sections of this chapter will describe the proposed system through a case study which shows the process planning module through a case study part which has milling and turning operations.

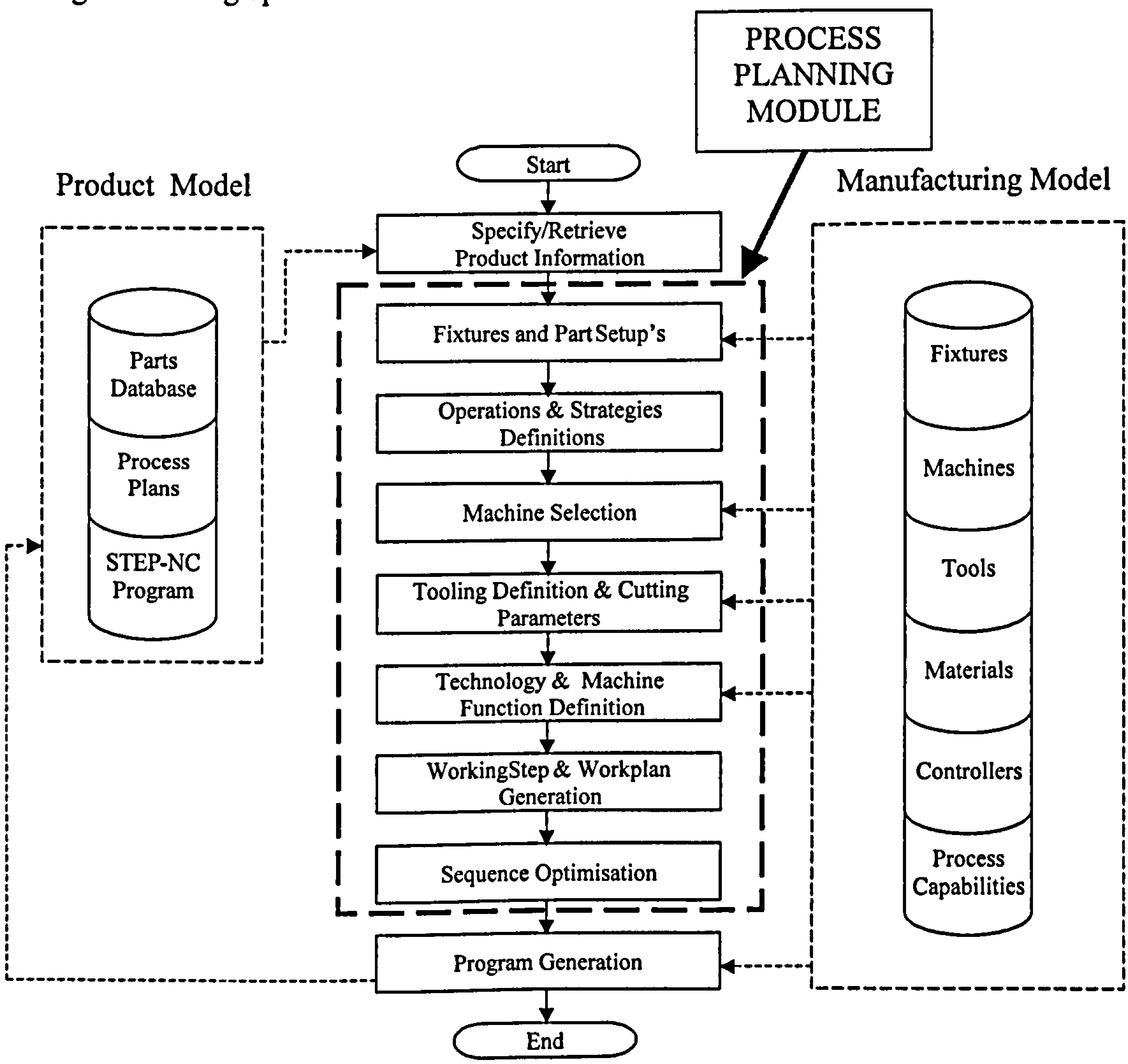


Figure 8.1 -The operational structure of the STEP-TM CAPP System

8.3 Case Study

An industrial oriented case study component has been developed to illustrate and demonstrate both the prototype system and supporting information models. The component shown in figure 8.2 consists of turning features defined in STEP terminology as out diameter to shoulder, revolved flat, revolved round, grooves, thread together with milling features such as slots and holes applied on the revolved surface of the part. The slots are created as a circular pattern around the piece and the holes as individual entities.

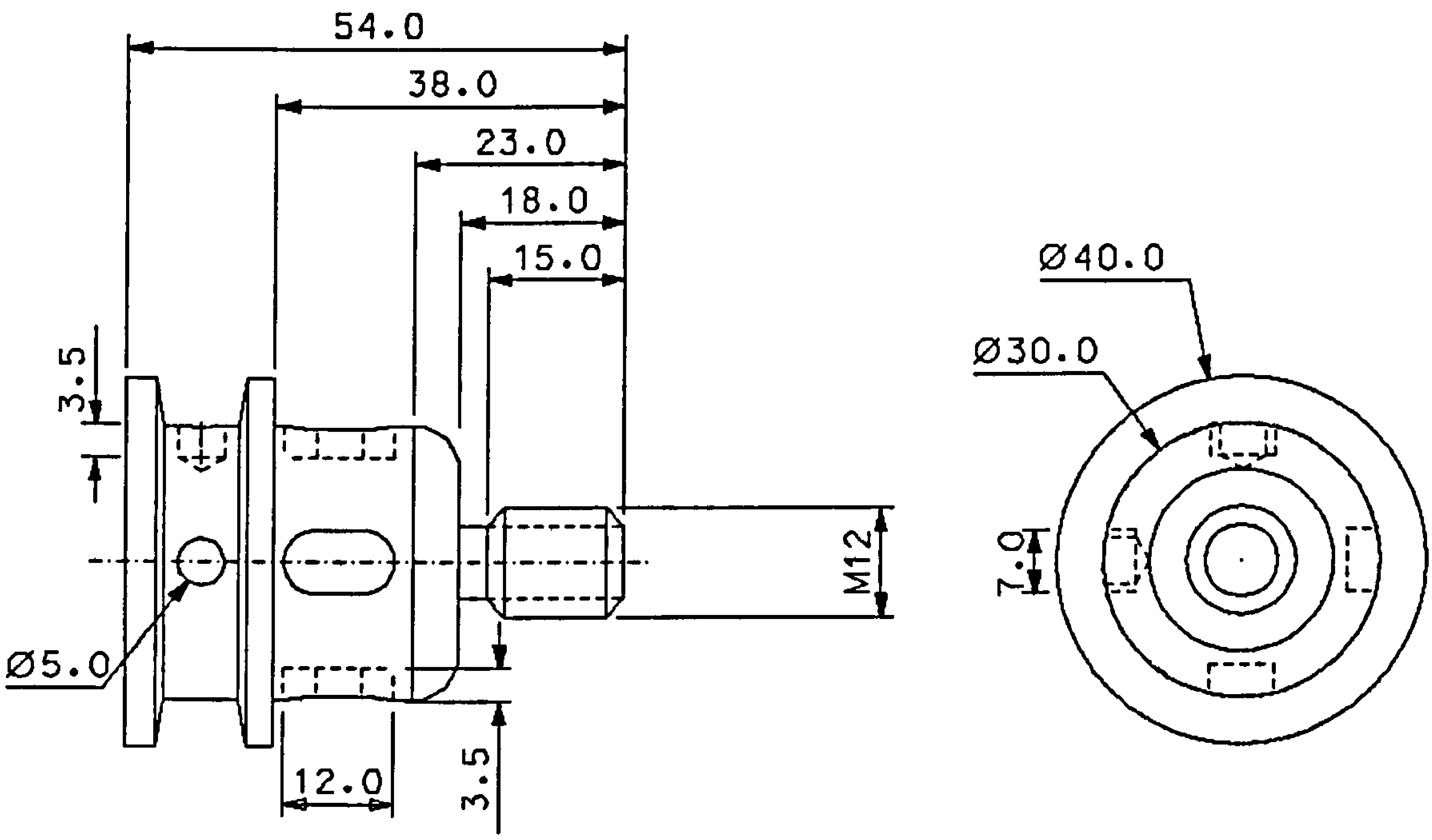


Figure 8.2 - Case study component with milling and turning features

This component obviously requires a mill turn CNC tuning centre to be efficiently manufactured in a single machine visit. It has been designed specifically to enable testing of the research on a C axis CNC turning centre with live tooling.

8.4 System Control Interface

The major interface of the prototype system enables the activation of the various options through the main menu. This menu is illustrated in figure 8.3 and consists of four pull down menus namely: File, Data Maintenance, Process Plan and Program Generation.

- File menu : provides the functionalities to Save a process plan/program, Save a process plan partially created (this means with no program generated), read the product information, delete a product information and read a STEP-NC program for editing in the Process Plan Module.

- Data Maintenance menu allows access to the same name module which maintain the persistent data of machines, tools, fixtures, process, materials and the possibility to visualise the workstation information as a whole.
- Process Plan menu empowers the user to create process plans in automatic or interactive mode. It also provides the functionality to edit and delete a process plan that is in the working memory.
- Program Generation menu enables the user to generate a STEP-NC program or a machine specific program in a non STEP-NC code. Figure 8.3 depicts the menus of the system control module.

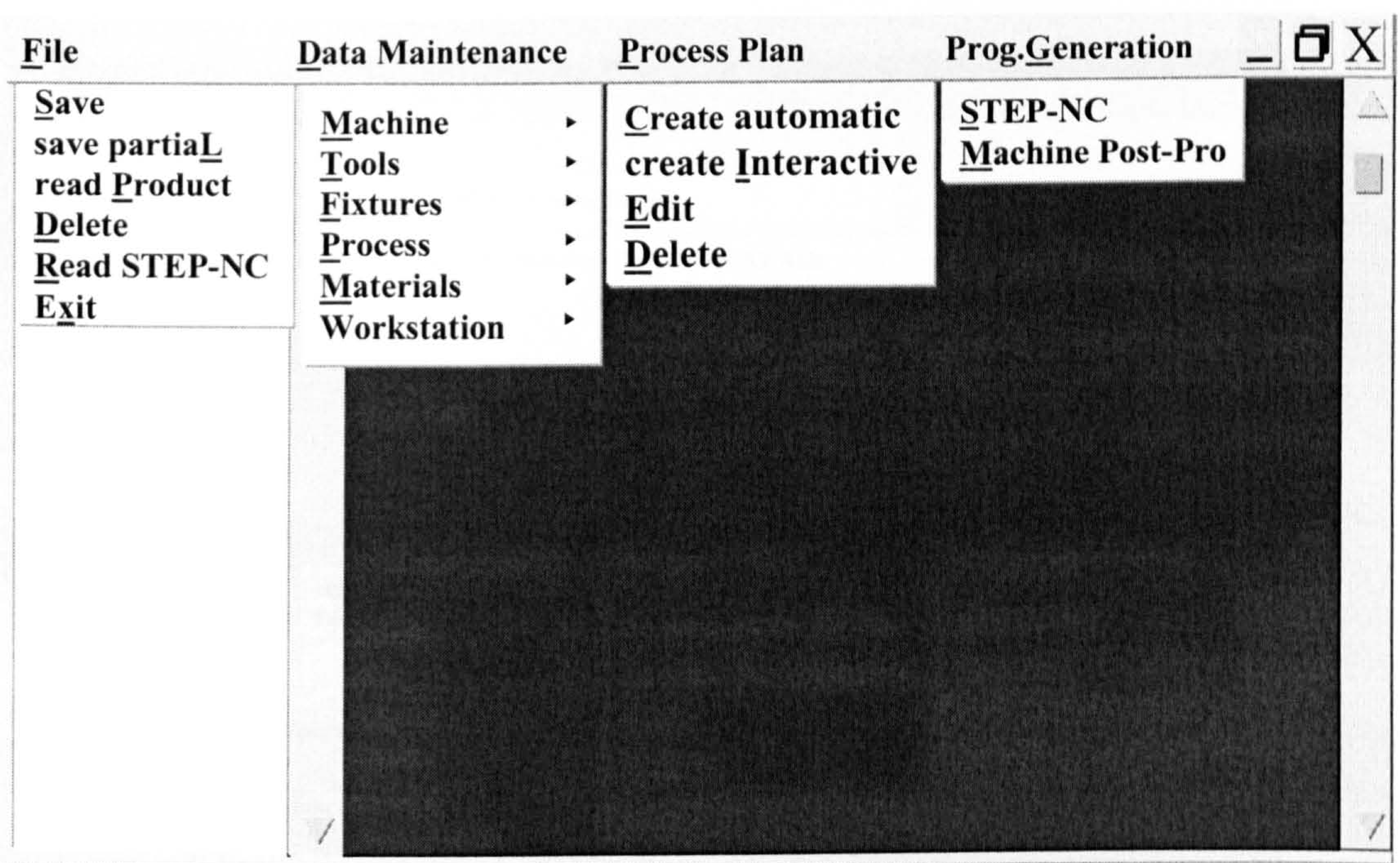


Figure 8.3 – Main screen of the STEP-TM CAPP showing the four menus available

8.5 Data Base Maintenance Module

As the system is based on the information held in the STEP compliant model, it needs to have a persistent data repository. A maintenance module is provided to enable functionalities for the user to add, edit, delete and visualise the information. It is based on the use of an Object Oriented Data Base Management System to manage the information as STEP information is "object flavoured". However, relational databases could be used using middle layer drivers such as the ODBC technology. The figures 8.4 to 8.9 depict the user interface to administer the information in the data repository and their relationship with the manufacturing model developed in this research work.

Figure 8.4 represents the dialog for editing the top level of information for the CNC turn/mill workstation. The dialog has been designed based on the manufacturing model introduced in Chapter 7 and depicted in figure 7.4b. The user is able to define and edit machine data representing the types of axes, number of spindles, turrets, turning machine sizes/capabilities together with other information such as process capabilities and raw materials. Figure 8.5 illustrates the design origins of the work showing the manufacturing model UML representation of the data for the linear axis of a turning workstation.

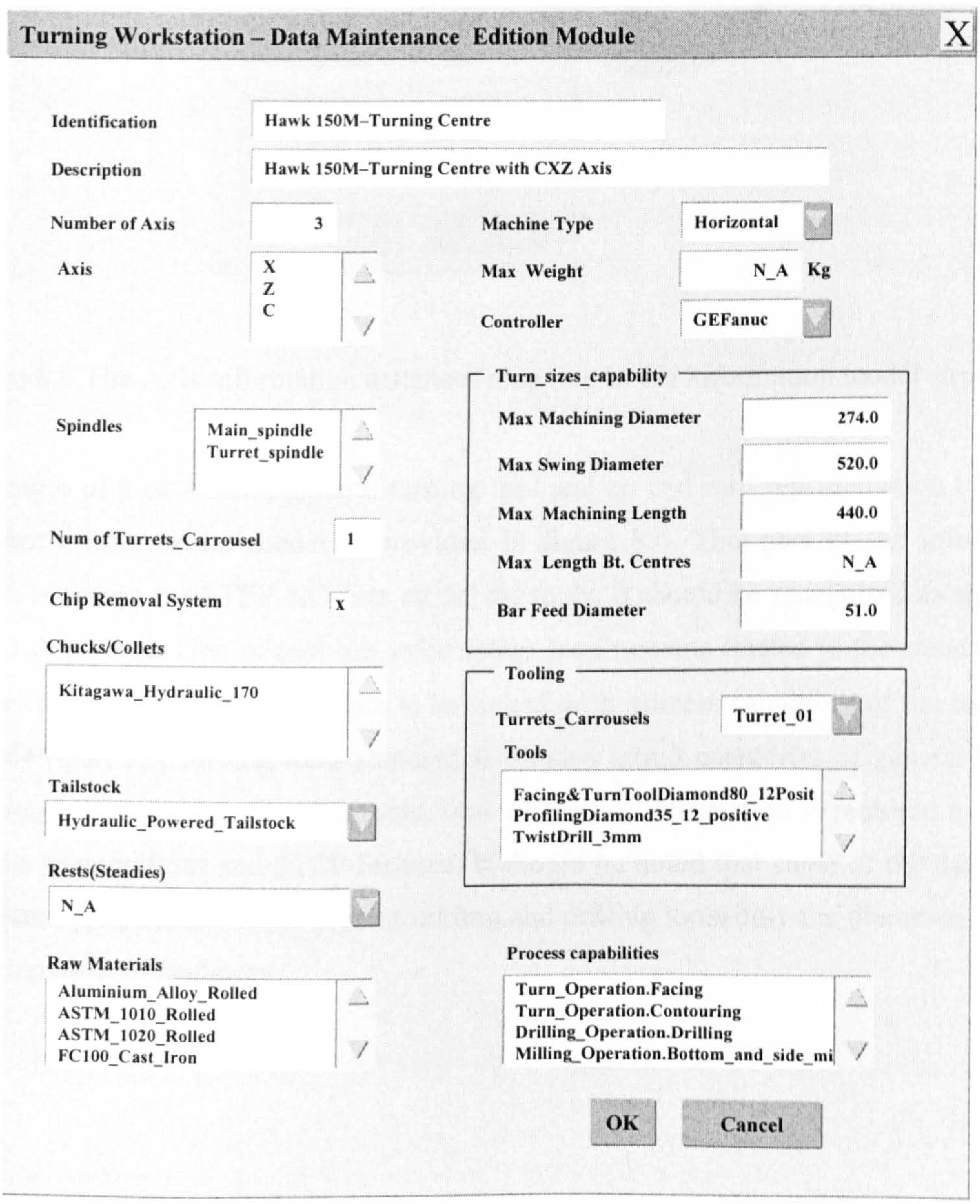


Figure 8.4 – Dialog to edit the complete workstation.

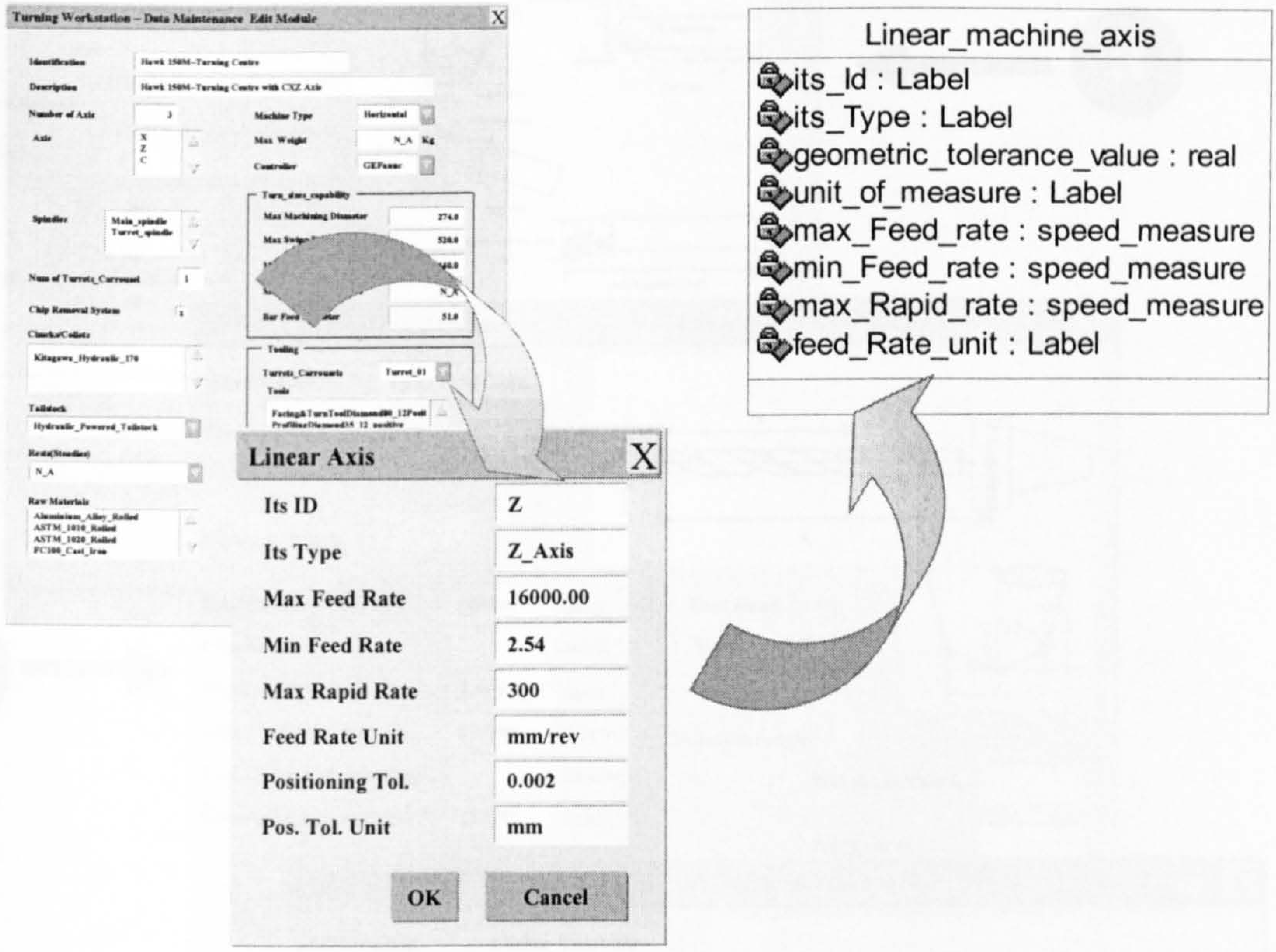


Figure 8.5 The Axis information instances mapping in the information model structure

An example of a twist drill, general turning tool and an end mill representation based on the author's information model is provided in figure 8.6. This part of the information model is based on the STEP-NC data model for tools. It should be recognised as shown in the figure that each kind of tool has information requirements related to the standard, but has been extended to enable the data to be linked with process capability of the tool. The ISO 14649 part 121 turning tools standard is divided into 3 categories of general turning tool, threading tools and grooving tools, thus additional information is required to enable link tools to operations and STEP features. It should be noted that some of the data fields are optional for instance, in the case of milling and drilling tools only the diameter, and the overall length are mandatory.

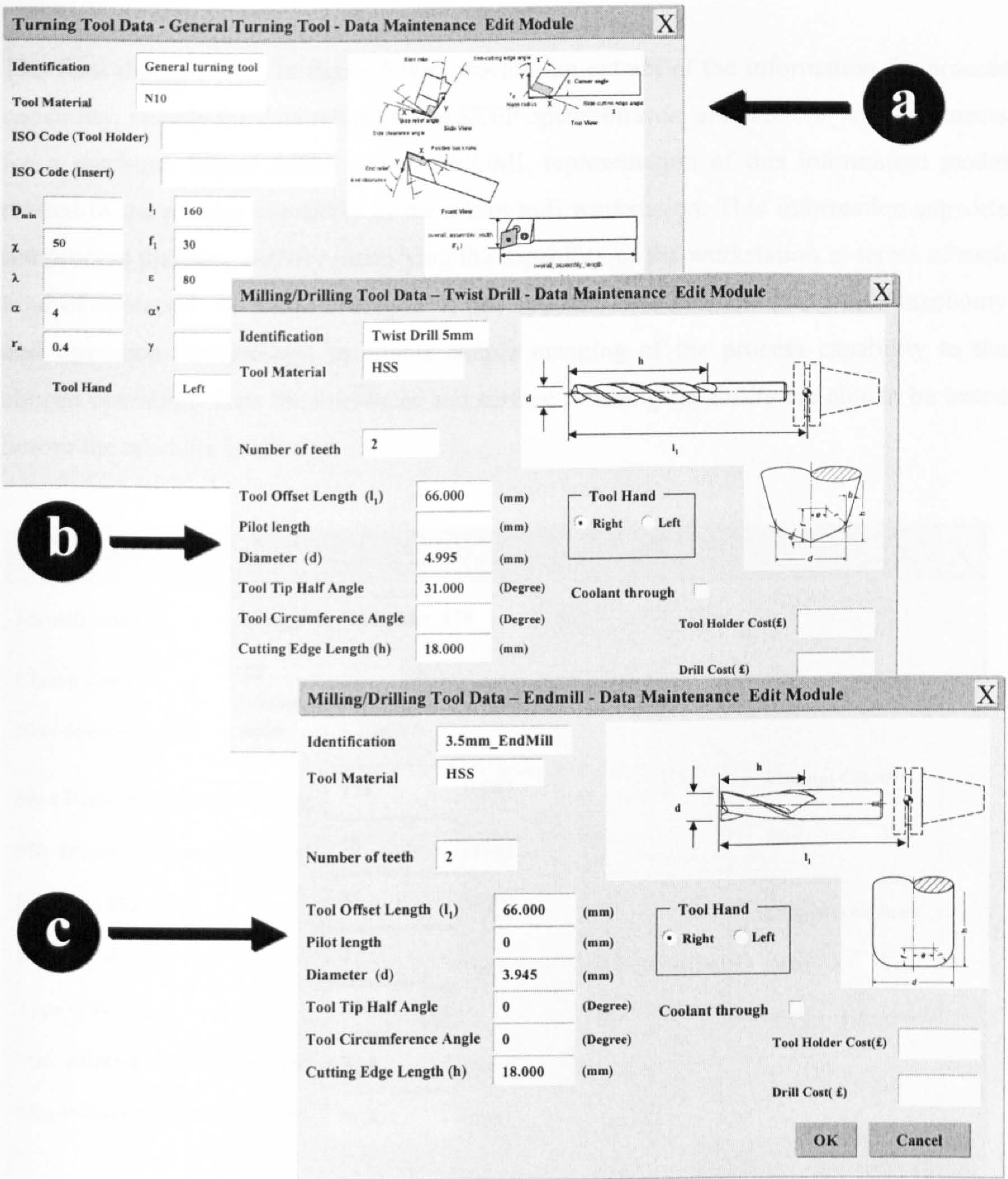


Figure 8.6 - Tool data dialog in the examples of a general turning tool(a), a twist drill(b) and an endmill(c) depicted

The data requirements for fixtures are depicted in figure 8.7 and represent data relating to chucks, tailstocks and steadies (termed rests). The example dialog shows the data definition for a 3 jaw chuck. Figure 8.8 provides the data requirements which represents the component raw materials for use on that workstation which is based on the AP224/AP240 definition.

The final dialog shown in figure 8.9(a) provides an extract of the information for process capability, namely the data related to the STEP operation *side_and_bottom_milling* process for a machine. Figure 8.9(b) shows the UML representation of this information model related to the process capability of the a turn-mill workstation. This information supports the process planning activity identifying the capability of the workstation in terms of each kind of operation. As stated in chapter 7, this structure uses both the ISO 14649 taxonomy and operation terminology, to enable simple mapping of the process capability to the chosen operation. Thus the tolerances and surface finishing capability are able to be tested before the machine is selected.

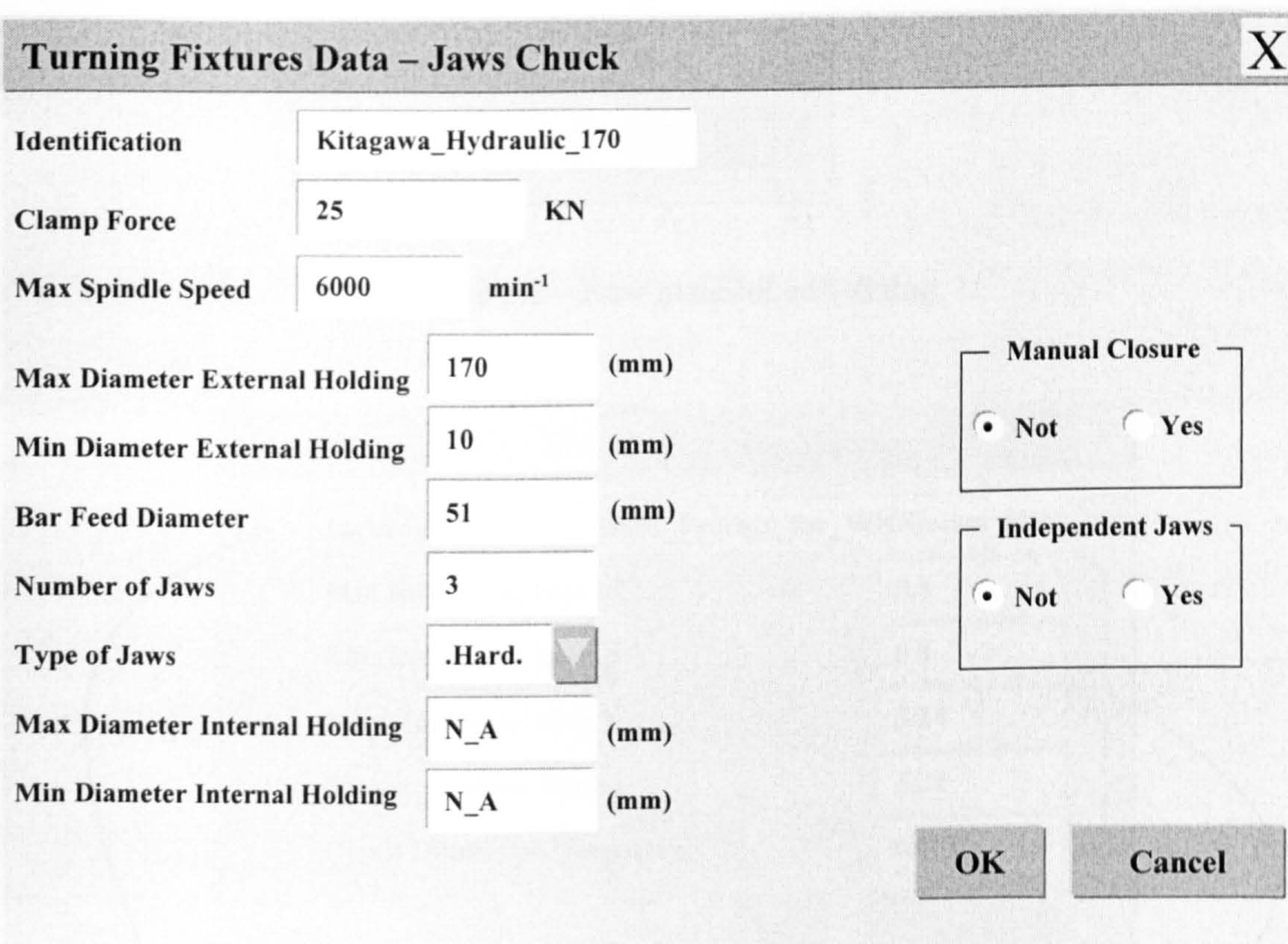


Figure 8.7 – Turning fixtures data dialog displaying a 3 jaws chuck data

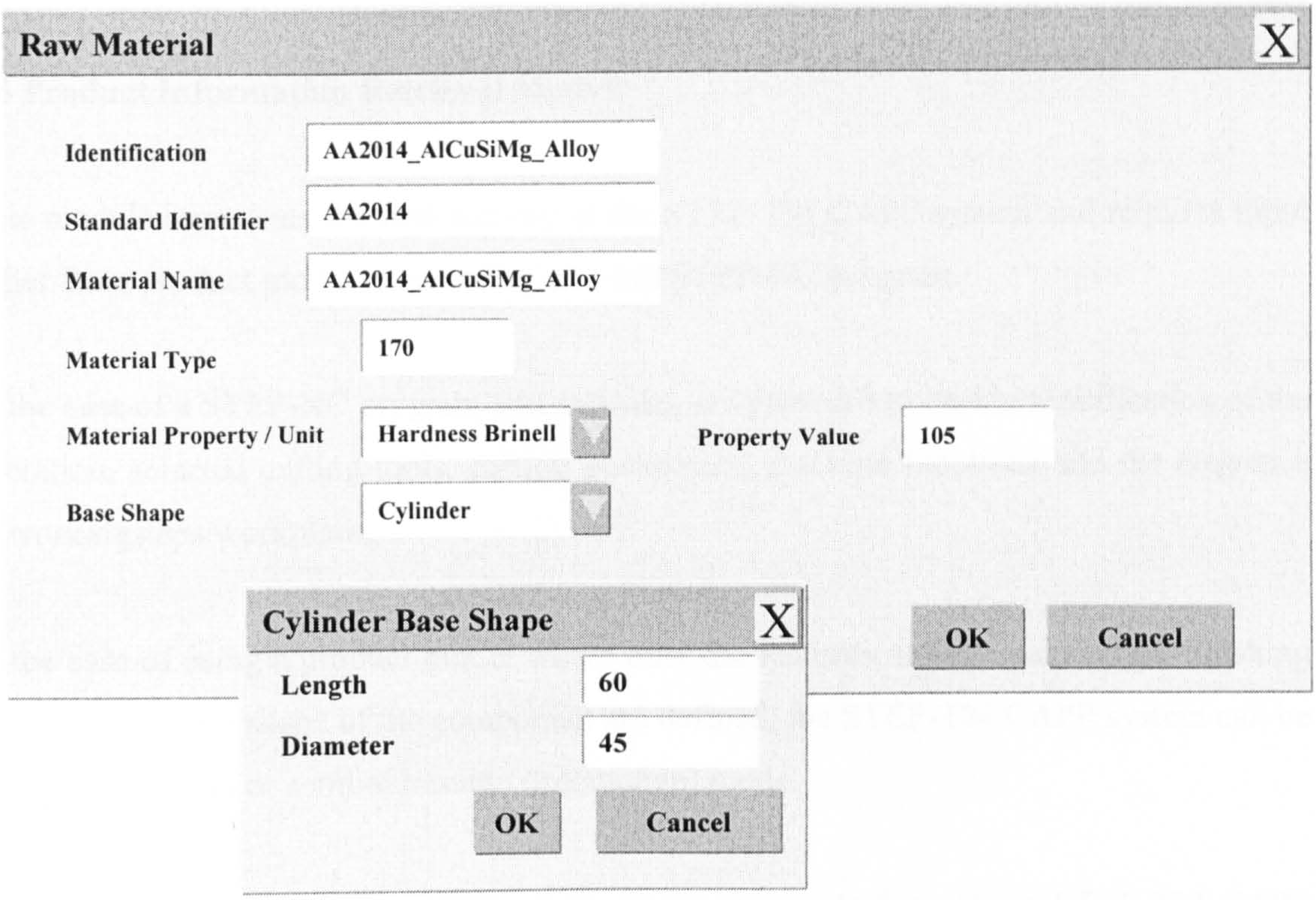


Figure 8.8 – Raw material edit dialog

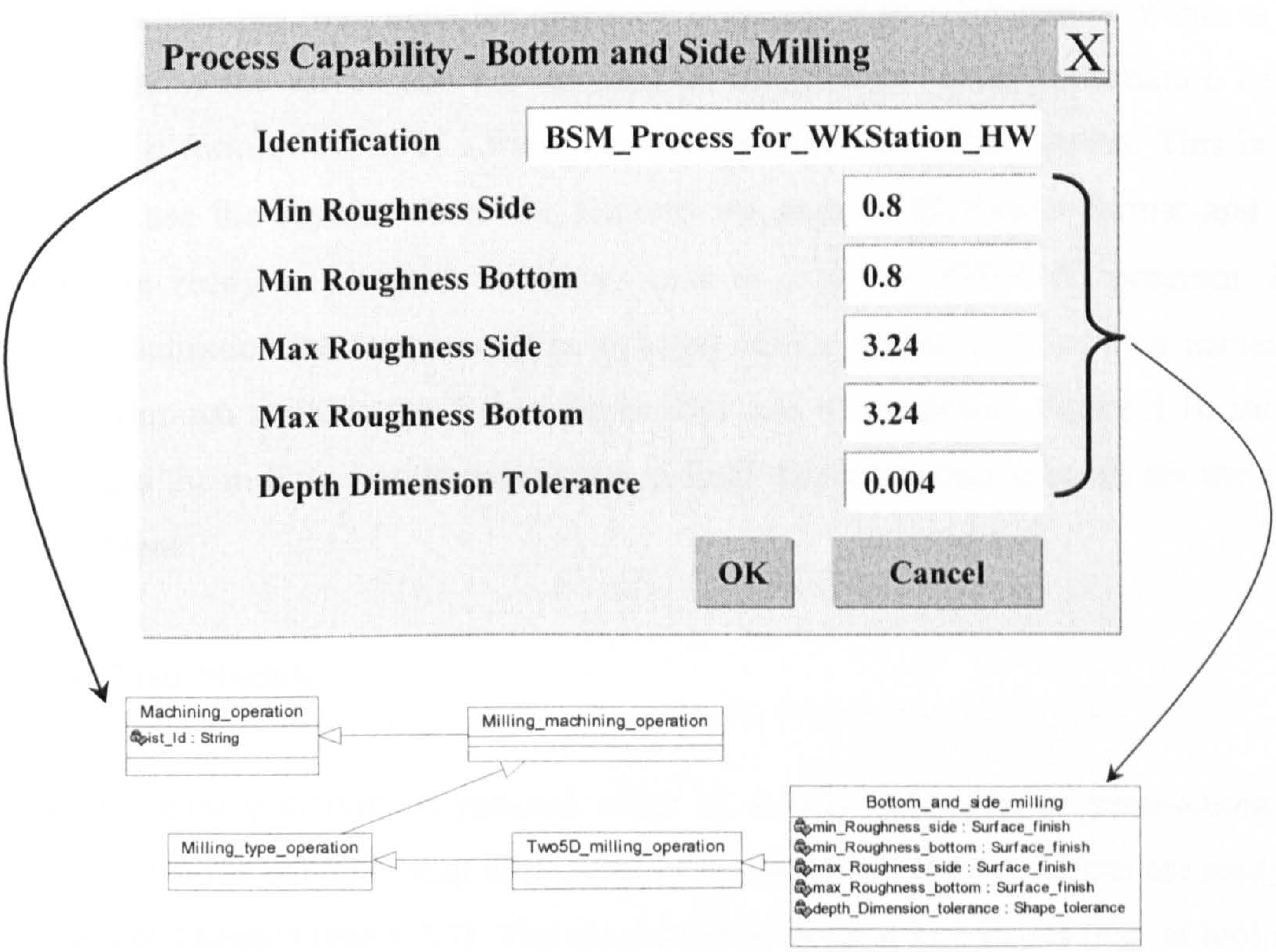


Figure 8.9 – Process capability edit dialog with mapping in the UML model

8.6 Product Information Retrieval Module

This module represents the first activity of the STEP-TM CAPP system and requires input either from product model information or a full STEP-NC program.

In the case of a STEP-NC program edit facilities are provided to enable modification of the operation, selected cutting tools, cutting parameters, machine functions and the sequence of workingsteps/workplans.

In the case of using a product model where only the features, tolerances, surface finishing and material, base shape of the component are defined, the STEP-TM CAPP system can be operated in a fully or semi-automatic (interactive) mode.

This option is provided via the File menu in the main interface of the STEP-TM CAPP system as shown in figure 8.3. This is the main screen of the system, which stays available throughout the process as most of the interaction is provided by dialog boxes. Once the product information has been input the geometry is displayed in a 3D graphic frame at the right hand side of the screen and the contents of the product model information being displayed in the form of a tree in a frame on the left hand side of the screen. This is the start point to use the system where the features are read in ISO14649 format and the parameters are ready to be used in the process to create a STEP-NC program. For parameter visualisation the features can be selected with a double click on their names in the tree and through a dialog the feature parameters can be displayed. Figure 8.10 shows the turning and the milling feature parameters in their respective dialog boxes for the case study component.

8.7 Process Plan Module

The process planning activity is realized either in a fully automatic or semi-automatic mode. The first mode will only stop when a set of *workingsteps* and *workplans* are ready to be optimised or changed (see 8.7.7). The second mode stops at key stages (e.g. at tool and cutting parameters selection) allowing the operator to interact and change the decisions made by the system. In the following sections the key stages are outlined through dialogs which are displayed by the system at each stage of user interaction.

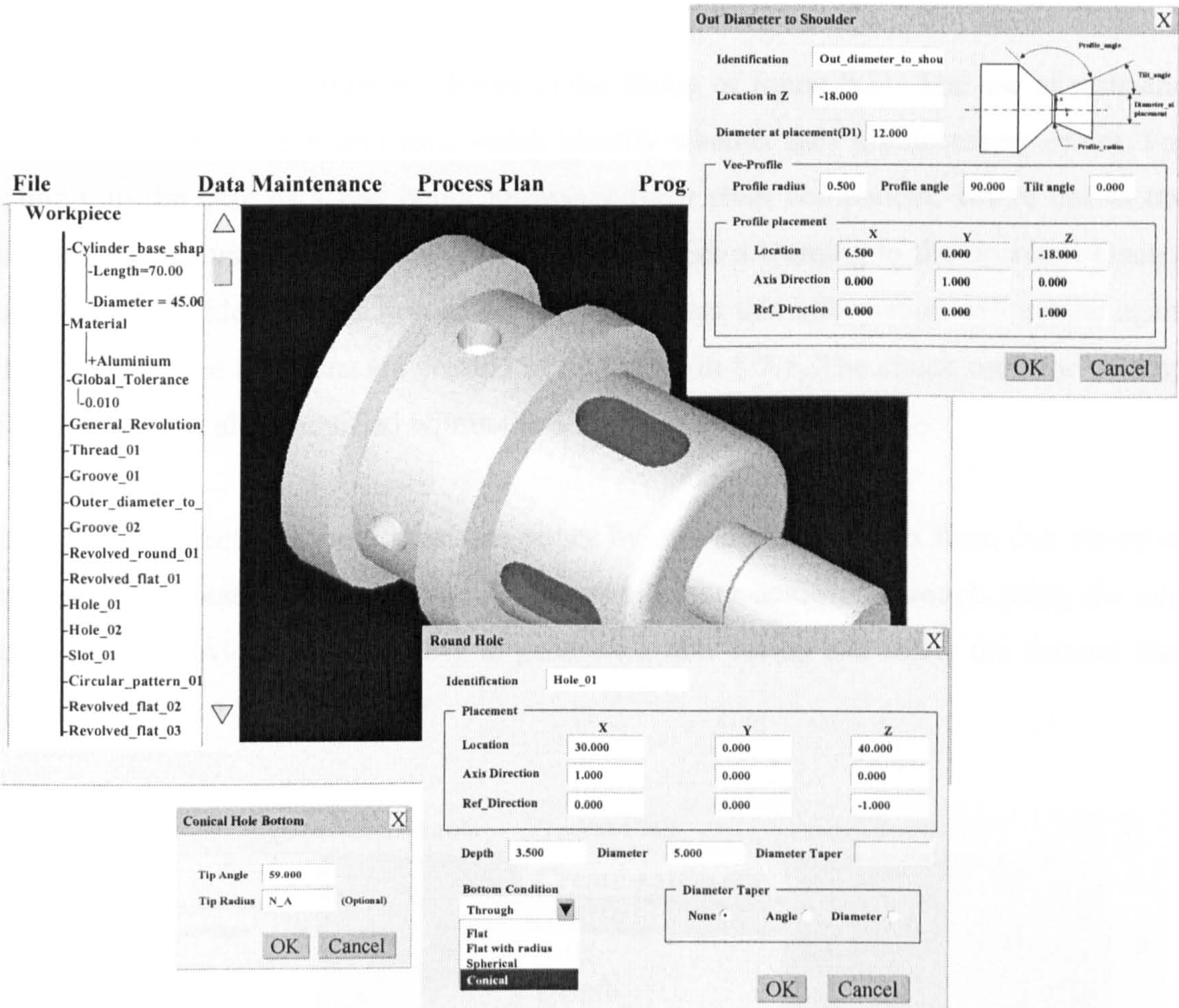


Figure 8.10 – Product information illustrating the STEP geometric definition

8.7.1 Fixtures and Set-ups Selection

One important function in process planning is to decide on the type of work holding device to be used(Varvakis 1991). In the case of rotational parts the decision on the use of chuck types, tailstocks and rests (steadies) affect the whole process. The number of set-ups is also of vital importance as it is decisive in the creation of the *Workplans*. The STEP-TM CAPP system takes the decisions in the following sequence:

- Analyse the need for a rest and/or tailstock based on the criteria of diameter/length ratio

- Organise the features by the placement position from the right to the left and search for problems in accessing the features in the set-up
- Create lists of features which will be machined in each set-up

The results of these activities are shown in the dialog of figure 8.11. The use of rests and tailstock are just Boolean decisions which identify whether they are necessary or not. For example in the case of a rest being necessary for a shaft component, where one is not available for the machine, a small dialog pops out with a warning to the operator. Once a fixture has been identified as needed for the component this information will appear again when the machine functions are created as described in 8.7.5. The chuck used for holding the component is also identified within the STEP-TM system.

The user can select and modify set-ups either by moving the features from one set-up to another or by creating a new set-up. These changes are achieved through using the edit function that provides the capability to generate a new set-up and select the features that will be moved to a second set-up.

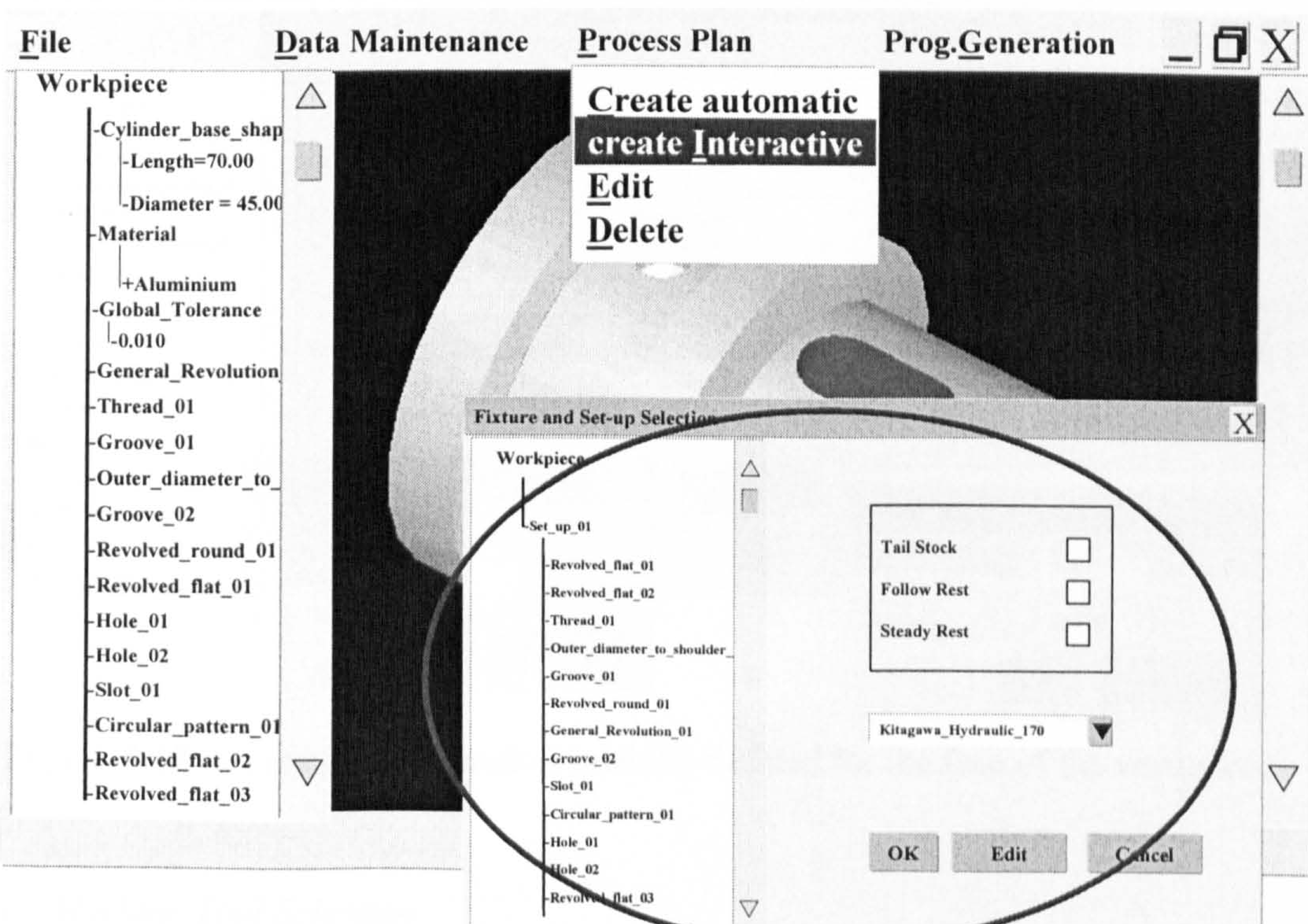


Figure 8.11 – The distribution of features in one set-up and fixtures selection in STEP-TM CAPP/CAM environment.

8.7.2 Operations and Strategies Definitions

This functionality in terms of STEP-NC relates to the Process Selection and Operation Definition mentioned in Section 7.8.3. One advantage of STEP-NC is the fact that it is based on features and *Workingsteps*. The structure of STEP-NC features provides a parameter that is a list of operations which should be used to create the feature. As there is a limited set of operations for each feature the definition of any decision criteria(eg. decision rules) are much simpler than in a conventional CAPP/CAM systems. At this stage operations are selected as well as their respective strategies. The sequence of operations can be added to the feature in any order, as they are there only to identify that they are needed to manufacture the part. The sequence of these operations is given by sequencing the *Workingsteps* in the *Workplans* which is described in section 8.7.6. Figure 8.12 illustrates a typical roughing operation for facing a component which requires the data relating to material allowance and approach strategy for the operation.

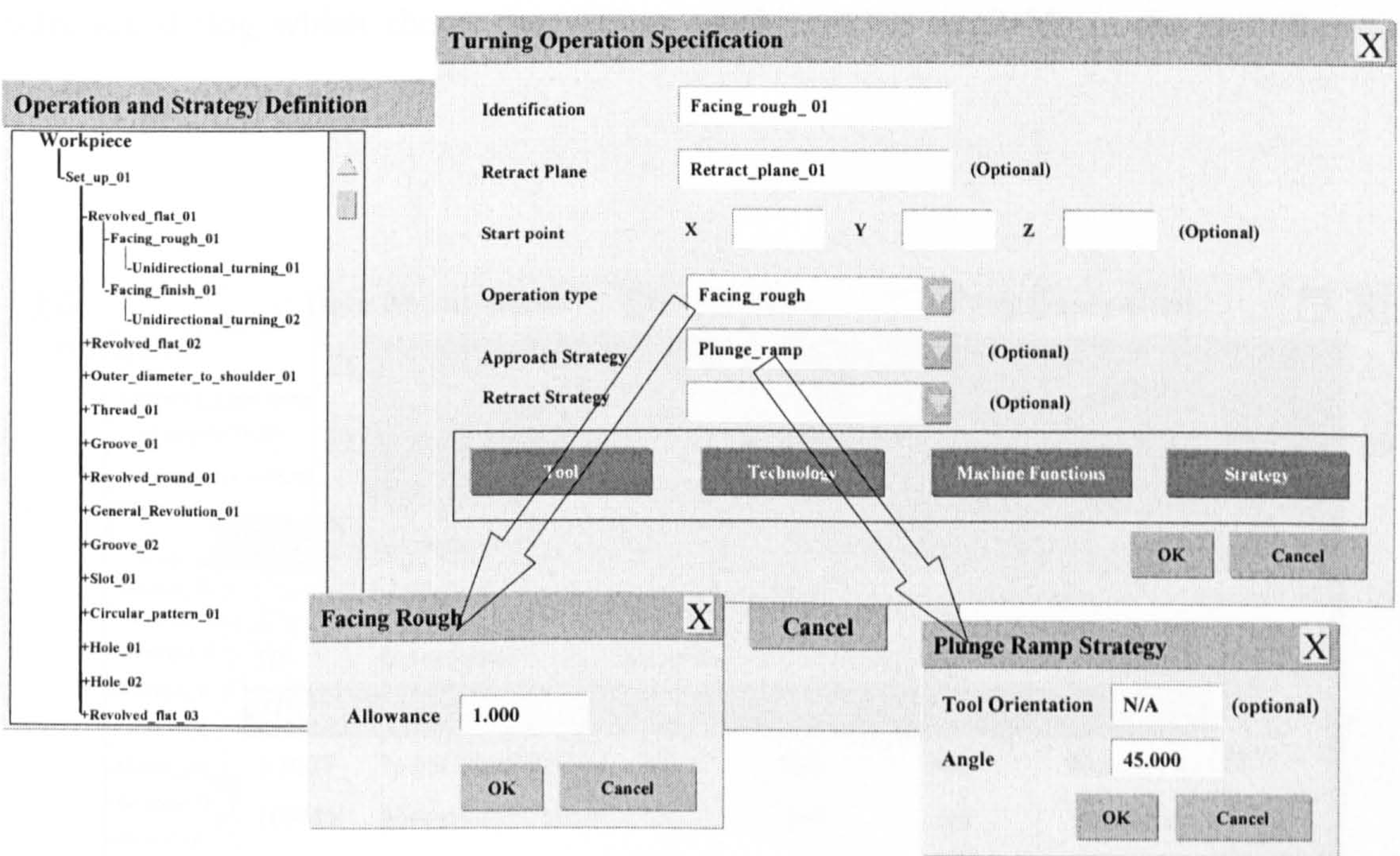


Figure 8.12 – A roughing operation partially defined for the face of the workpiece

8.7.3 Machine Tool Selection

In the case of the STEP-TM CAPP system the machine tool selection is optional. As non selection of a machine would endorse the philosophy of STEP-NC to generate an interoperable machine independent process plan. However, the author recognises that in many cases a planner would prefer to identify a specific machine available in the company. In this case the STEP generated program would take account of the machine configuration, and thus would be brought in line with the capabilities of the machine tool.

The decision to select a specific machine tool is based on the simple criteria that fully utilises the manufacturing model as that is where the capabilities of the workstation are described (process and resources). It should be noticed that the process capabilities are key characteristics of this system as the analysis of capability is achieved not only by the global restrictions of the machine tool but also by taking into account the capability of the workstation to perform each operation to the required constraints. This novelty provides a more accurate decision as the machining of parts has different behaviour for different operations on a particular machine. Thus, the author believes that this analysis is better realised when considering the capabilities of the machine related to each type of operation rather than a general representation of a machine. Figure 8.13 illustrates the machine tool selection dialog which shows the various machine tools available in the manufacturing model.

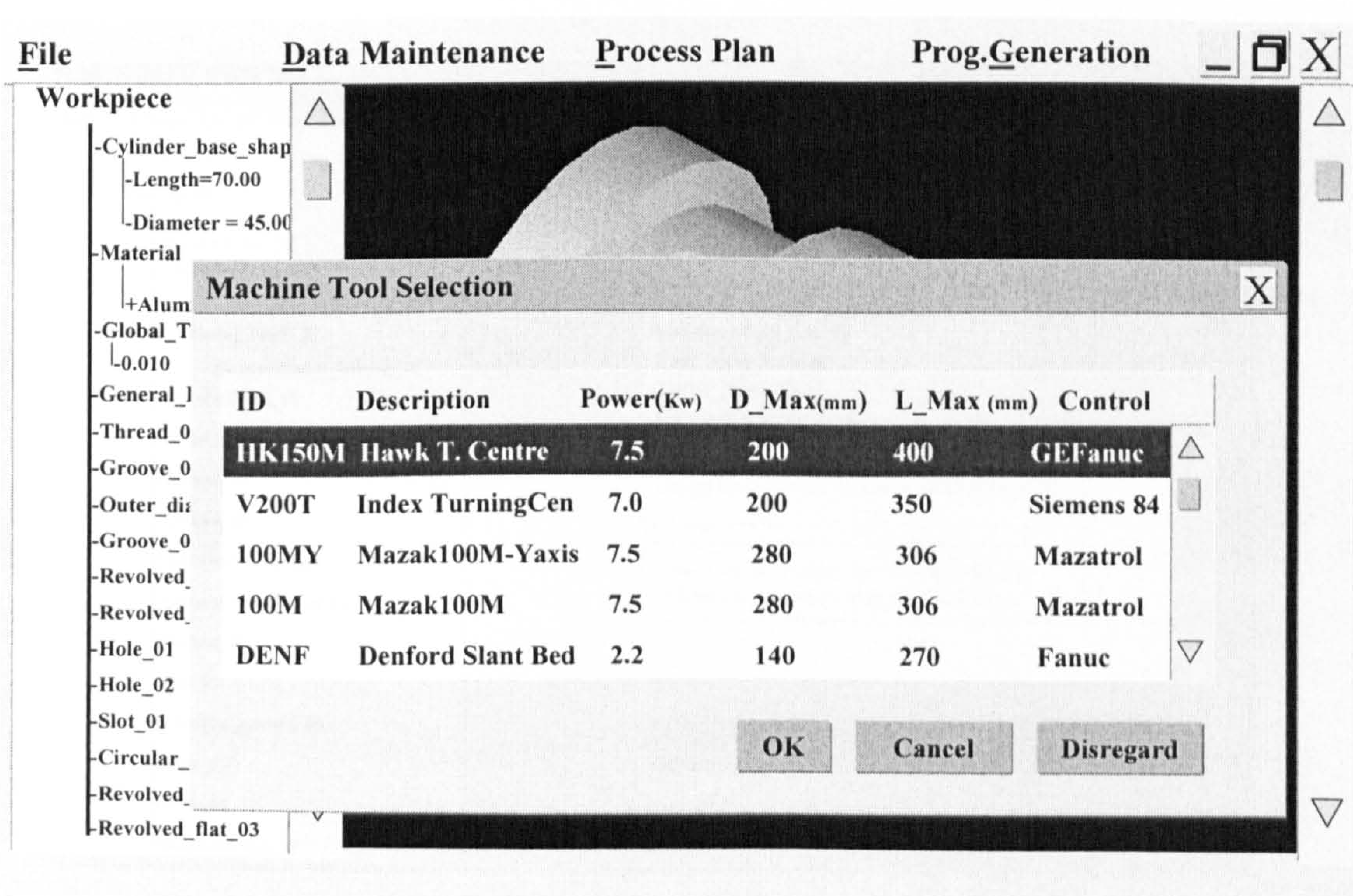


Figure 8.13 – Dialog for Machine Tool Selection

8.7.4 Tools and Cutting Parameters Selection

The cutting tools are chosen according to the operation and features that are being machined as well as the material of the part. The STEP compliant manufacturing model supports this activity as it holds information on raw material and the links with the tool material. The tools are also part of the resources that participate in the manufacturing model. The number of possible tools should be minimised to improve the performance either in terms of economy and time for tool change. However, tool selection is primarily achieved on individual pairs of feature and operation. Therefore, this may not necessarily provide the best performance in terms of tool changes and tool usage for the next operation. The optimisation is achieved after the sequencing of *workingsteps* and *workplans* as is described in section 8.7.7. The selected tools are linked to the operation in the STEP-NC schema.

The cutting parameters can be selected using the cutting parameters database, knowledge base or mathematical criterion such as the Taylor's Tool Life equation and Kienzle's equation as in Rosso-Jr(1995). The decision on what type of strategy to use in the cutting parameter selection is implementation dependent and the discussion is out of the scope of this work.

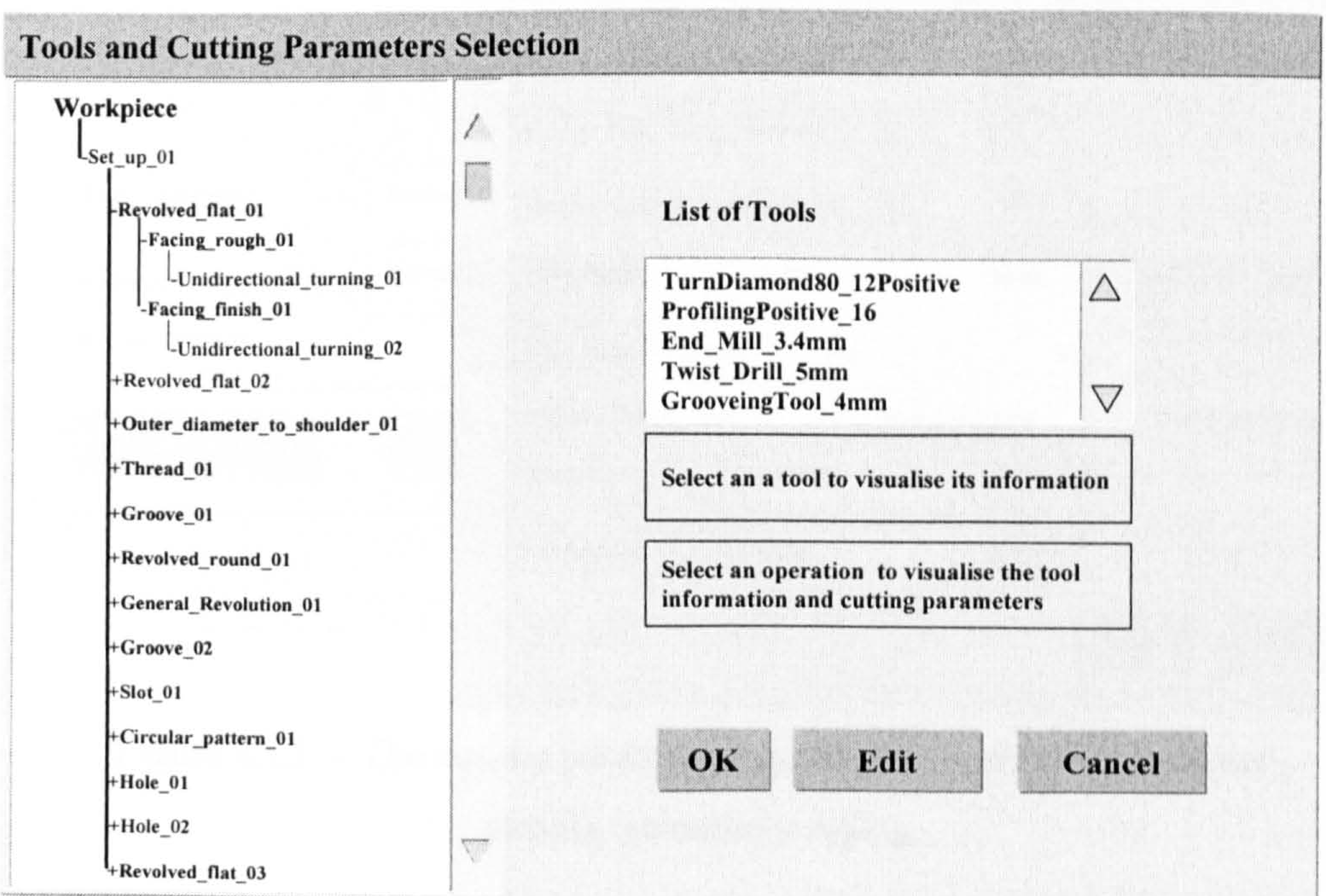


Figure 8.14– Tools and Cutting Parameters Dialog

The tools selected are displayed in a list as shown in figure 8.14. As the cutting parameters are chosen they can be visualised on the dialogs of turning technology and turning strategy. Figure 8.15 shows the turning technology dialog with the selected cutting speed and feed. It should be noted that the maximum spindle speed(RPM) which is a machine constraint is read directly from the manufacturing model. Although the strategy is chosen earlier in the process planning, the cutting depth is available only at this point though it is has an influence in the selection of the other two parameters due to the power consumption of the machine tool. Moreover, it is dependent on the effective cutting edge of the tool. However, to be consistent with STEP-NC the cutting depth is optional, and can even be unselected in the case of its use in a STEP compliant CNC controller. Here the controller has the capability to select the cutting depth. Figure 8.16 depicts the unidirectional strategy with the multiple passes parameter and the cutting depth selected.

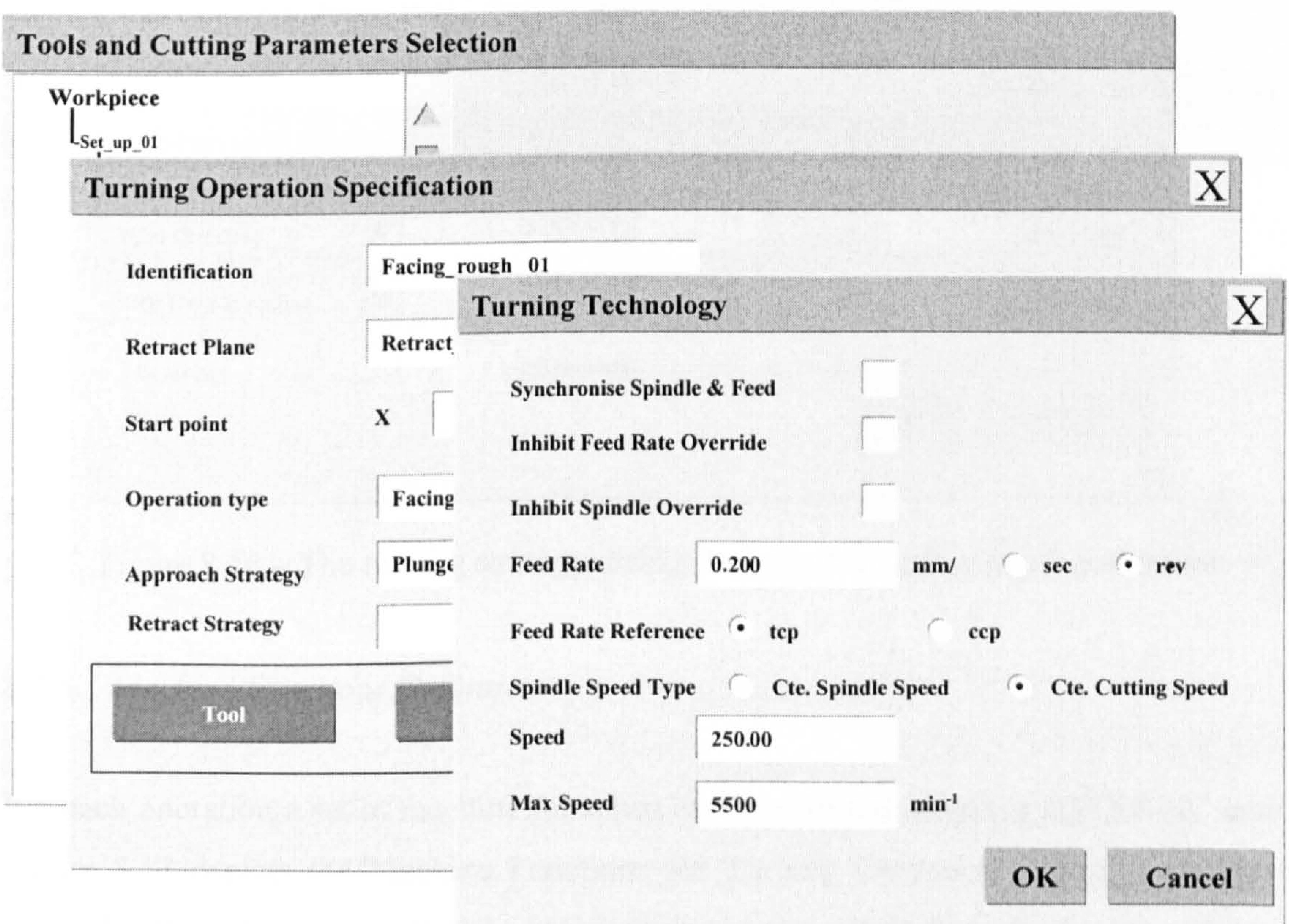


Figure 8.15 – The cutting parameters speed and feed available in the turning technology dialog

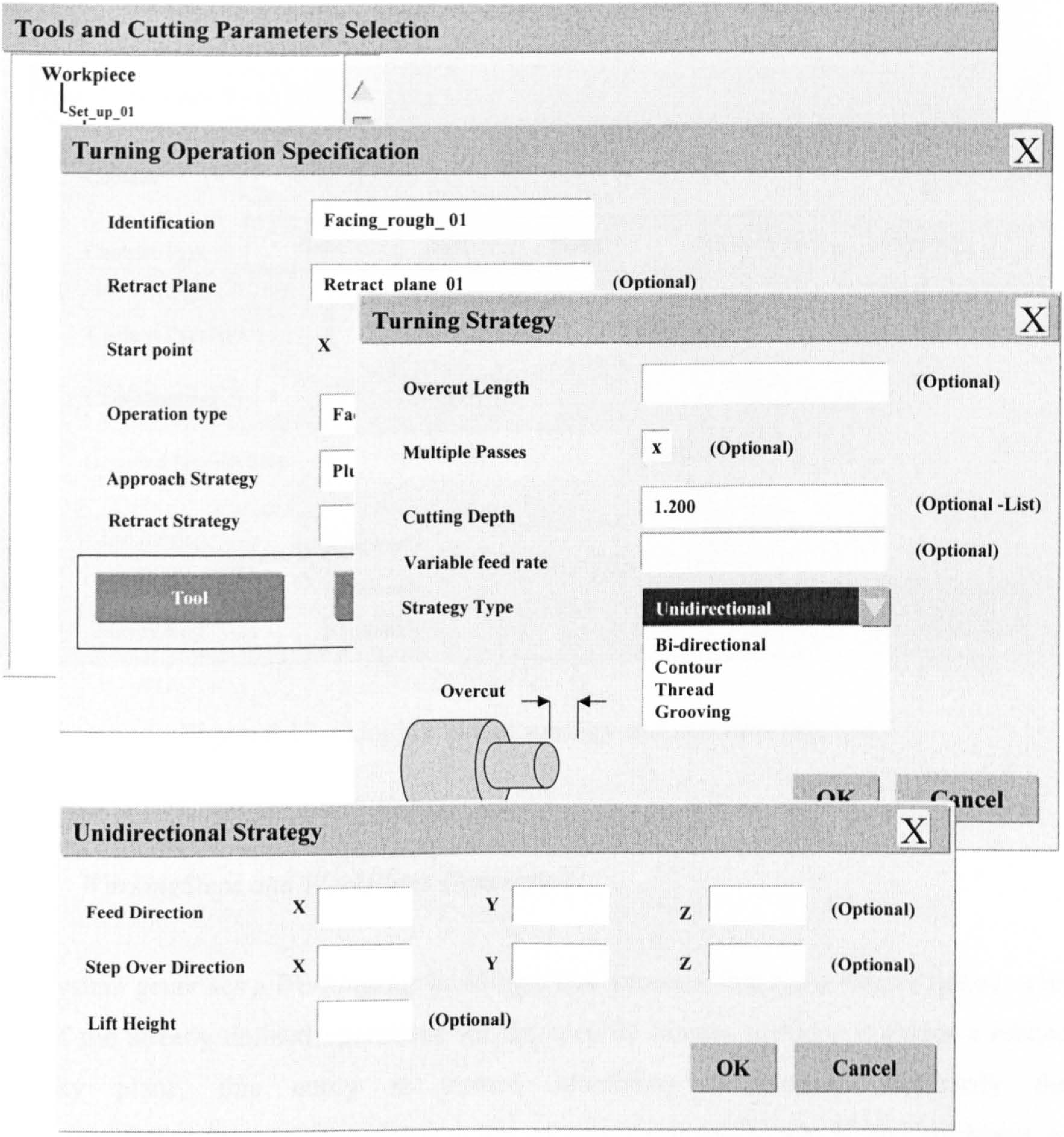


Figure 8.16 – The turning strategy dialog showing the cutting depth parameter

8.7.5 Machine Functions Definition

For each operation a set of machine functions can be selected as this is a STEP-NC entity. Figure 8.17 depicts the Machine Functions for Turning Operation dialog. It should be noted that the options about the use of tail stock and rests come from the fixture and set-up selection but are stored in this part of the STEP-NC structure. Most of the parameters are optional then, it is a choice of the user to set them or not.

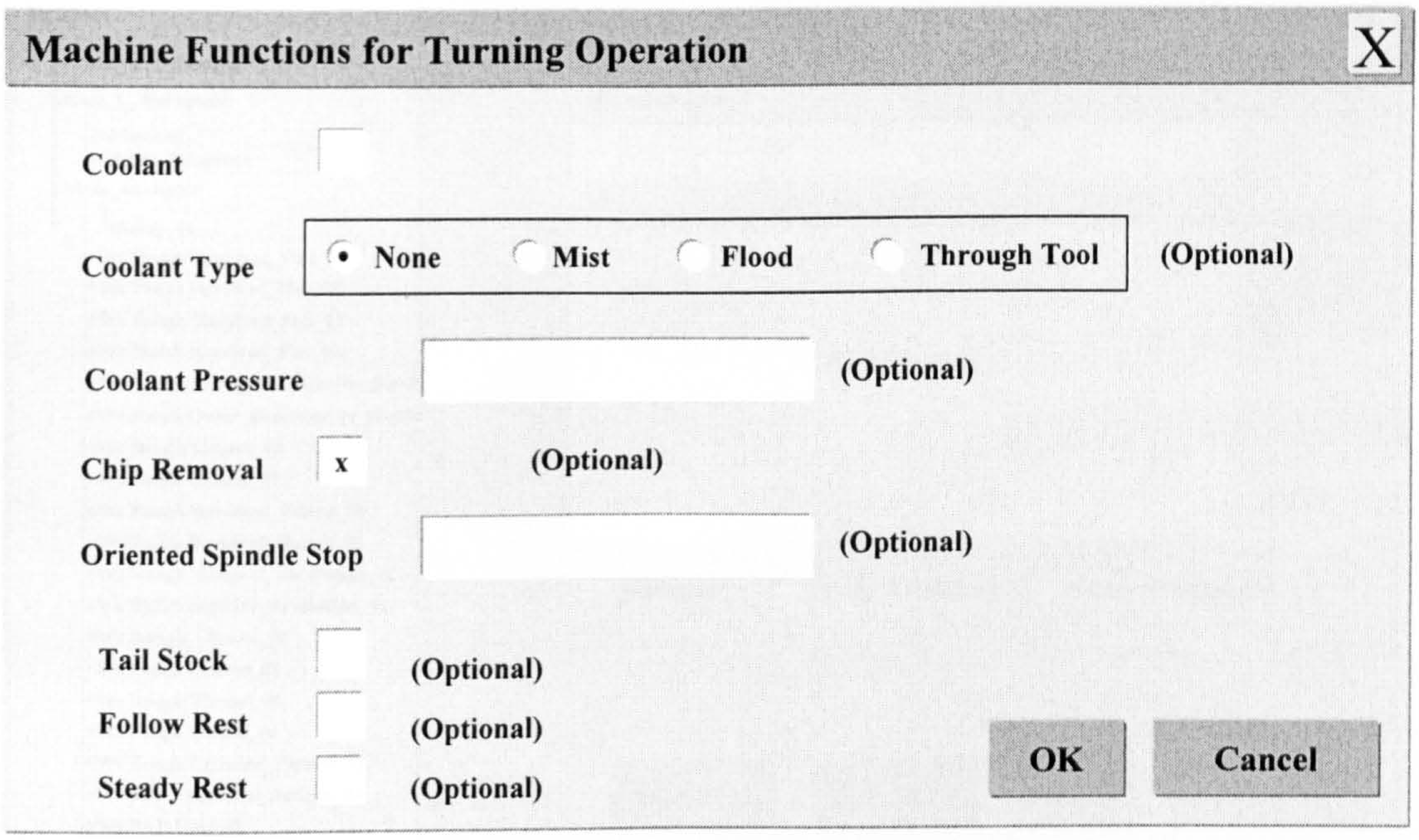


Figure 8.17 – Unidirectional strategy and machine function

8.7.6 WorkingSteps and WorkPlans Generation

The system generates a *Workingstep* building a tree structure that has a feature linked with one of the already defined operations for the specific feature and also includes a related security plane, this entity is termed *Machining_workingstep*. Contrarily the *Turning_workingstep* accommodates a list of turning features which are machined in sequence using the same operation, and is typically recognised as a contouring operation. The *Workingsteps* are then organised in the *Workplans* following primarily the set-ups defined in the early stages of the process planning activity and then the criteria of precedence of roughing operations over finishing operation. Figure 8.18 depicts the dialog that appears just after the *Workplan* has been created.

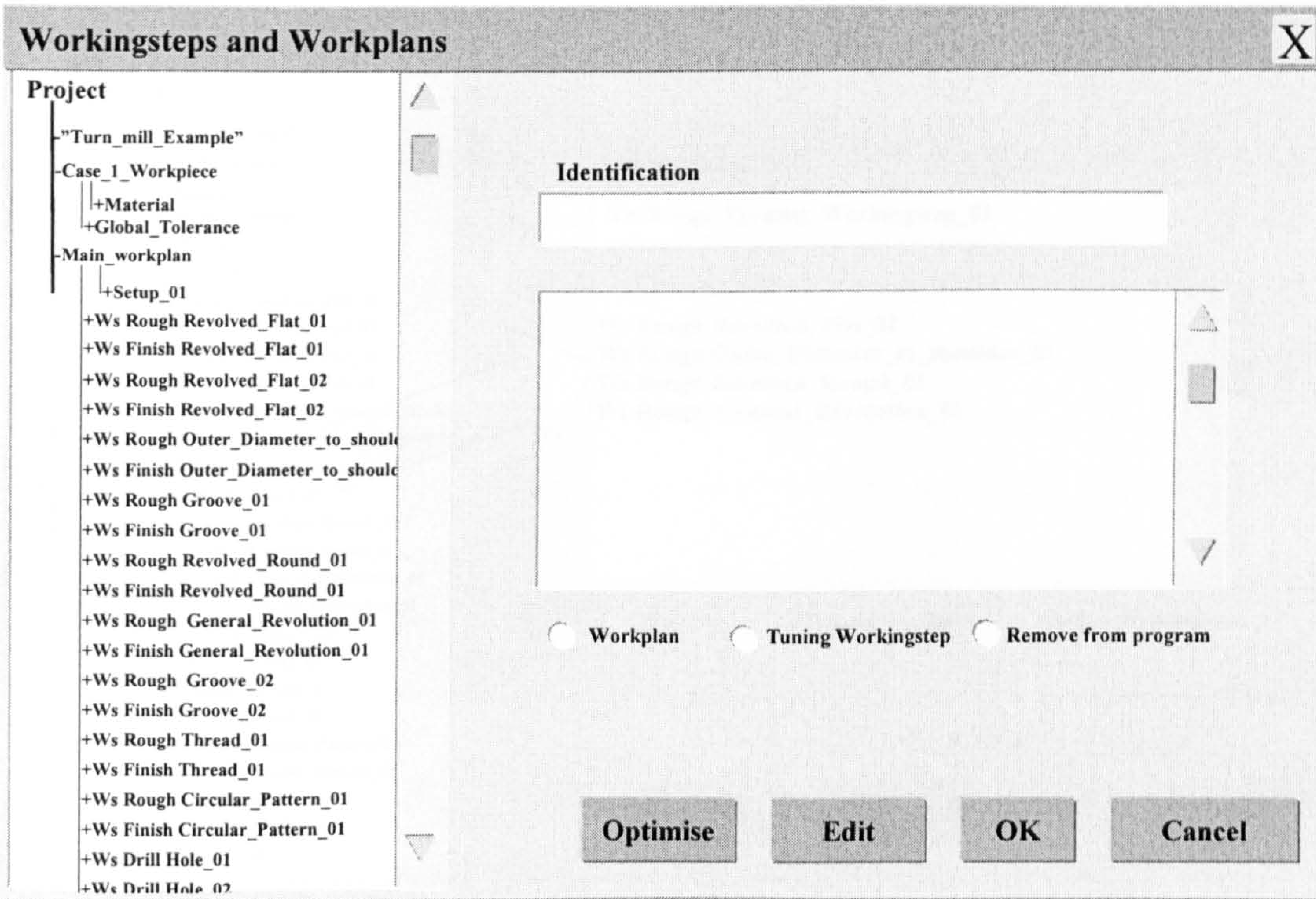


Figure 8.18 – *Workingstep* and *Workplan* creation and optimisation

8.7.7 WorkingSteps Sequencing and Optimisation

As the system has no optimisation algorithm the *Workingsteps* sequence in the *Workplan* may not be the best solution. Apart from this, a number of connected *Machining_workingsteps* can be transformed in one *Turning_workingstep* where a single operation is performed over a list of connected features. As commented previously, the *Turning_workingstep* improves the performance of the STEP-NC program as in general turning features are machined together by a contouring operation. The sequence and optimisation dialog also provides the functionalities to create a new *Workplan* and also enables the removal of *Workingsteps* and *Workplans.* Figure 8.19 shows two sets of *Machining_workingstep* which can each become a *Turning_workingstep* by moving them into a list box and giving an identification to the new object. The result can be noted in figure 8.20.

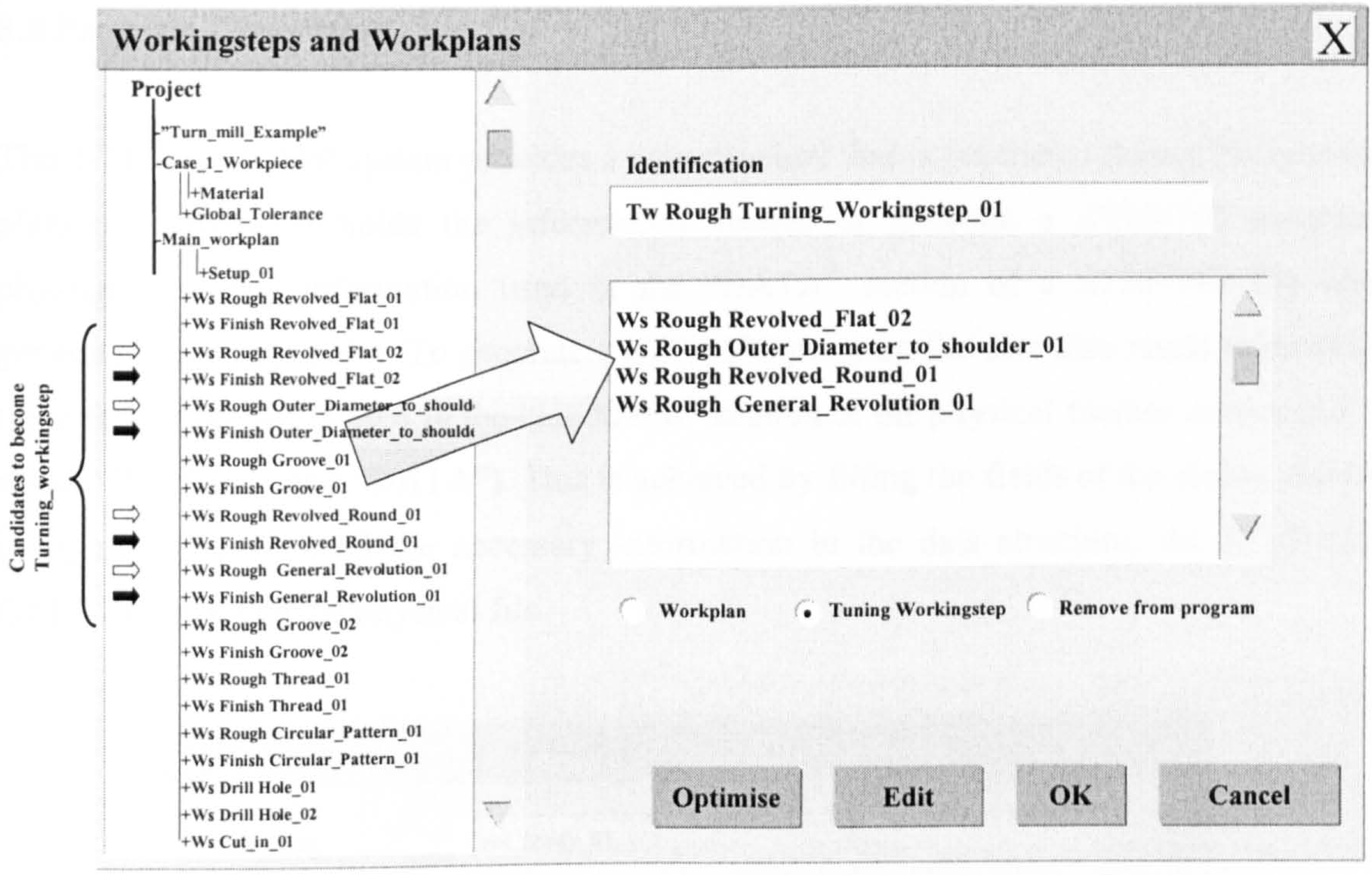


Figure 8.19 – The creation of a *Turning_workingstep*

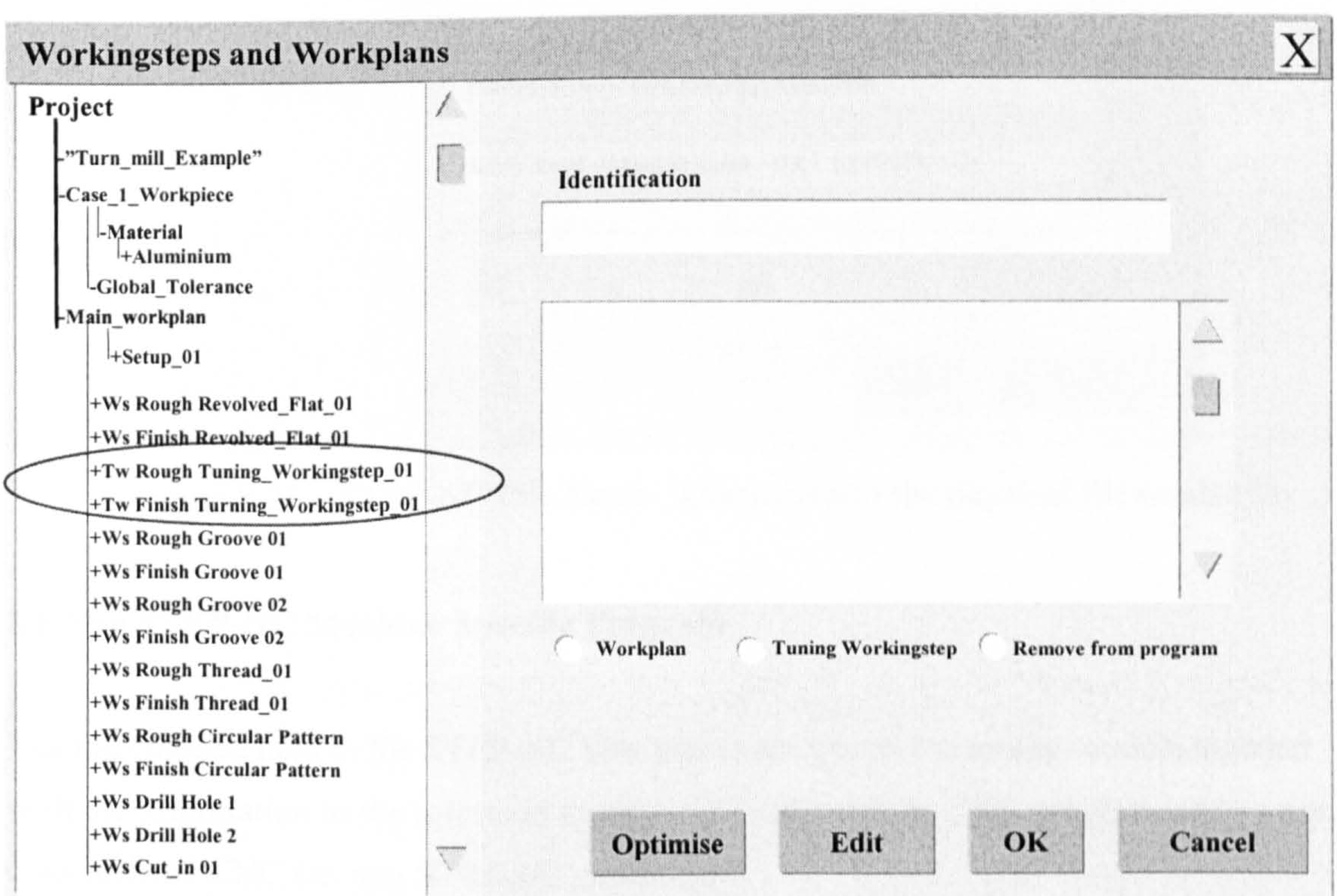


Figure 8.20 – The new workplan with *Turning_workingsteps* created from sets of *Machining_workingsteps*

8.8 Program Generation

The STEP-TM CAPP system provides a data structure that is populated during the process planning activity, it holds the information needed to generate a STEP-NC program physical file. The information used in the "DATA" section of a STEP-NC file was generated up to this point. To generate a STEP-NC program the user also needs to provide the information that is used in the "HEADER" section of the physical file(see section 5.5.1 about "HEADER" and "DATA"). This is achieved by filling the fields of the dialog shown in figure 8.21. With all the necessary information in the data structure, the STEP-TM CAPP can generate the physical file.

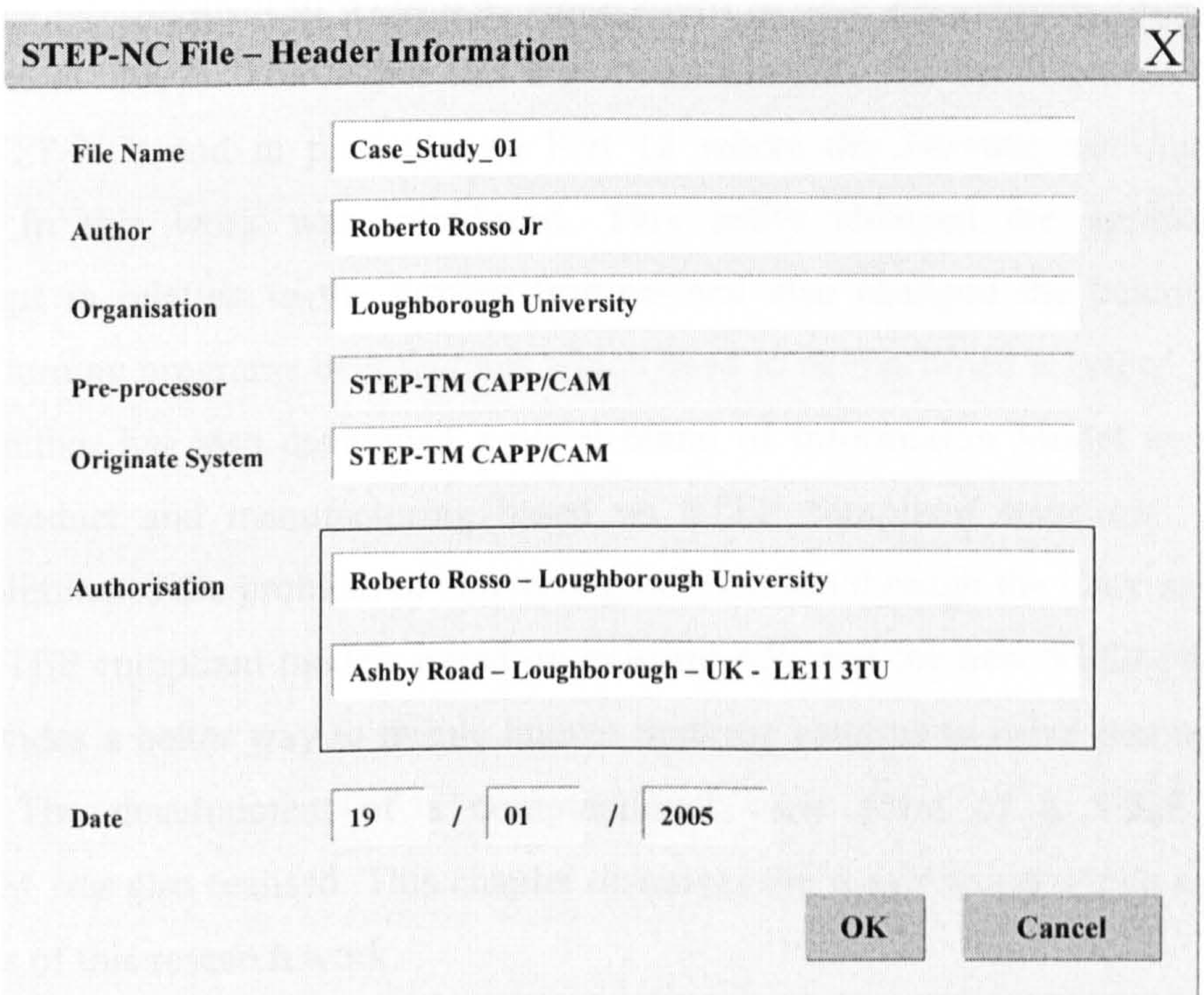


Figure 8.21 – STEP-NC File Name information to the physical file header

8.9 Non STEP-NC Machine Specific Program

The information held in the STEP-NC structure in the process planning module together with the information in the information model is used to create a NC program using a non conventional CNC (ie. non STEP-NC controller).

Chapter 9

Concluding Discussion

9.1 Introduction

This research was carried out during the time of the rapid development of the STEP-NC standard, it has generated a number of frameworks which were published in 2002 which represent the development of STEP-NC applications to date and possible future scenarios (Rosso-Jr et al. 2002). The author has also contributed to the development of the ISO 14649 (STEP-NC) and in particular to Part 12 where the *Turning_workingstep* entity developed in this work was introduced. This entity changed the approach of the workingsteps in relation to the turning features and also changed the behaviour of the STEP-NC turning programs over features which need to be machined together. During this work the author has also developed a novel brand of Information Model to represent a turn/mill product and manufacturing based on STEP compliant standards. This novel approach eliminates the problem of converting information through the CAx process chain by using STEP compliant models based on existing APs and the new STEP-NC standard. It also provides a better way to mimic human thinking patterns to solve process planning problems. The development of a computational view point of a STEP compliant CAPP/CAM was also realised. This chapter discusses the major issues which establish the conclusions of this research work.

9.2 Review the literature relating to STEP standards, CAD/CAPP/CAM/CNC and features based research

The literature reviewed in chapters 3, 4 and 5 has indicated the emergence of the continuing trend over the last three decades to automate, integrate and standardise the data sharing/exchange activities between CAx applications. Based on the growing amount of the literature it is clear that it is still an area of research interest.

From the pioneering research on feature technology to today's approach of STEP compliant information standards data exchange is still a major research issue. STEP-NC provides a real opportunity for the integration and sharing of interoperable information across the design to manufacturing chain. The specific development of STEP towards manufacturing gives vendors and users the chance to empower the next generation of intelligently controlled machine tools.

Though information models have been a research area for some time, the question of interoperability has always been an issue. Even using STEP standards the lack of appropriate Parts related to the manufacturing side was a problem recognised by the author in the literature (Jurrens et al 1995; Ashworth et al. 1996 and McKay et al. 1997). Though the body of work in product modelling is much more expressive than in manufacturing modelling, the recent developments of ISO related to manufacturing features and CNC data interfaces, namely AP 224 and ISO 14649 have opened a new avenue to support this problem.

Though significant research in STEP-NC has been undertaken in the areas of Milling and Turning individually, this thesis reports research carried out in the area of STEP compliant turn mill component manufacture which has received little or no attention to date.

9.2.1 STEP-NC standards development

The initial releases of STEP standards were based on the constructs of the standards and in general related to Product representation on its own. Examples are the 40's series and the initially released application protocols. Though it was not covering the whole life cycle, in recent years a move in the direction of the manufacturing with the development of ISO 14649 brought the opportunity to have STEP in the manufacturing part of the product life cycle.

STEP-NC brings forth the long awaited opportunity to empower the next generation of machines tool through the deployment of standardised geometric and manufacturing information at the machine tool. For the full adoption of such a paradigm shift from the traditional NC culture the major concern is the need of the user trust the machine tool as no tool path generation is necessary in the STEP-NC program.

9.2.2 Comparison of STEP-NC and programming methods

Based on the literature reviewed a comparison on the use of STEP-NC, CAM system and ISO 6983 manual programming has been developed by the author and is shown below.

Comparison Issues	STEP-NC	NC part Programming System	Manual Part Programming
Programming Level	Highest Level Command	High Level Commands	Lowest Level NC Code
Program length	Similar Length to manual part program, but has Different Data	Not really applicable but data stored in Cam system format in Software	Efficient for tool paths when combined with Canned Cycles/sub-programs, can be very long for 3D parts
Part Description	ISO Standard using Geometric Features	Software Specific Pseudo Standard	No part geometry in Code
Technological Description eg Tool definition & speeds	Tool Definition to ISO standard & cutting tool Parameters	NC System holds database of Tools and cutting parameters	No Tool Description accept Tool Pocket or Tool Assembly Code
ToolPaths	Not Described, left to intelligent Controller	Toolpaths simulated shown and output through post Processor	Tool paths information based on Tool Centre Line
Readability	Easy to Follow and read major process operations, complex data statements	Easy to follow operations and uses Dialogues and High level language	Lowest Level commands with XYZ and G and M codes
Surface/3D capability	Not defined as yet in detail	Based on 3D solid Geometry, Surface Machining now standard	Possible but program needs processing from Cad/Cam systems
Machine Tool Description	Little definition of the Machine or its intelligence	No definition	No definition

Figure 9.1 – Comparison between the state of art NC programming and STEP NC

The author believes that the most important issue is the programming level which fully establishes the worth of STEP-NC is its high level of detailed process planning information with tools, speeds, feeds and fixturing been defined in the programme. The additional advantage of interoperability through generating tool paths codes at the machine tool is also worthy of note. It should be recognised that the full testing of interoperability and its validity has yet to be proven by the STEP-NC Community. Finally, the machine tool description and the description of intelligence in the controller are not specified in STEP-NC standard. This is the reason for the development of the author's manufacturing model described in chapter 7 and 8 of this thesis.

9.3 Specification of a framework to support a STEP compliant NC manufacture

Though the development of STEP-NC has created an exciting opportunity for integration in CAD/CAPP/CAM and CNC, it is the author's opinion that the mass utilisation of such a standard within a wide range of manufacturing sectors will not be possible in the immediate future. This is due to the reliance on traditional technology and trust in the current programming culture and the slow rate of change due to the high initial investments needed. As a result this research has defined 3 distinct frameworks which provide a road map for the current and future utilisation and development of STEP-NC.

The first framework illustrates the limited structure of early STEP-NC system prototypes of 2000-2001, which used STEP-NC as just an import and export facilities for STEP-NC code generation.

The author recognised that to take better advantage of the new STEP-NC standard it should not just be imported and exported from CAx systems but also needs to be represented internally within the systems. This is shown in the adoption of the second framework which shows the need to eliminate translations and the use of proprietary information structures in CAD/CAM systems. This provided the opportunity to create an interoperable data model related to features and manufacturing. The result being the second level of STEP compliance, shown in sections 6.3.2.1 and 6.3.2.2, which possesses the advantage in using standardised information structures. However this second framework also suffers with the number of internal information translations to enable proprietary data structures to be used in conjunction with STEP-NC.

To establish a fully compliant STEP-NC model the author devised the third CAD/CAM framework, outlined in section 6.3.3, which operates a internal STEP compliant information structure thus needing no translation with proprietary formats. This framework represents the author's view for the 'ideal' STEP-NC information system. Based on this framework the author has developed the STEP compliant information models for both product and manufacturing models outlined in Chapter 7.

The author believes that it would be difficult to convince industry to convert from today's commercial CAD/CAM systems to a fully STEP compliant (i.e. Framework 3) structure as there are 1000's of man years of development invested in the current proprietary solutions. Thus the adoption of the second framework solutions represents a more realistic next generation of STEP-NC solutions that are currently being developed (eg. STEP Tools 2005)

9.4 Explore the use of feature technology with a STEP compliant approach

Though there has been an enormous amount of feature related research in the areas of design and process planning. Due to the lack of manufacturing standards these pioneering works have not been developed significantly for feature based manufacture

The author's research has effectively demonstrated the applicability of the use of feature technology in the machining process supported by STEP compliant information models as this gives feature based connectivity from design and process planning through to machining

The research explored the use of the ISO 14649 and ISO 10303-224 set of features. The integration of the design and manufacture activities by the use of these two sets of standard features greatly enhanced the interoperability when compared with current methods. The need for harmonisation of the two sets is now accepted in the STEP community and was one of the issues raised by the author in the very early stage of contributions to the ISO14649. Currently this brings the overhead of information mapping, as the part of the feature model related to milling is not totally harmonised. However, the model for turning is already harmonised and it is the author's opinion that, as only a few features(milling) are not totally harmonised the sets are essentially the same in nature and can be used equally since a mapping table is used. These issues were partially explored by the author in Rosso et al. (2002), Rosso and Newman (2003) and Rosso et al. (2004).

From the beginning of the research an informal collaboration was established with the research groups of WZL-Aachen and ISW-Stuttgart in Germany which has provided access to updated information on the developments of STEP-NC as well as the possibility to better contribute in the build up of the standards. The comments from Loughborough University were prepared by the author and forwarded officially via British Standard Intuition(BSI) and informally directly to the aforementioned research groups. A side result of the research in features technology and STEP-NC standards was the author's development of the *Turning_Workingstep* structure (see Chapter 5) which changed the way STEP-NC turning program behaved and the treatment of a features set being machined together. This structure was accepted by the ISO committee and incorporated to the ISO14649 part 12 (turning data model).

9.5 To investigate and realise a STEP compliant information model for asymmetric rotational parts

From the knowledge and understanding gained throughout this research it has been apparent that the design and operation of a fully compliant STEP-NC CAD/CAM system relies on the definition of the information models to support the operation of such systems. This research has designed and generated two such information models namely the PM and MM based on structures defined within the STEP-NC standards. Such models are shown to provide an effective starting point for the design of a fully compliant STEP compliant CAD/CAPP/CAM system, and to store and maintain effective part and manufacturing data.

The information models described in Chapter 7 provide structures to standardised product and manufacturing models. The designed product model has been shown simple and effective to represent the product's design and manufacture information. The use of the STEP features as described in Rosso-Jr et al. (2004) have been shown to solve the question for the use of STEP milling features together with the STEP turning features. The use of integrated STEP compliant structures, for each aspect of the PM has been demonstrated to be effective and facilitates the data input in the CAPP/CAM.

The Manufacturing Model has been shown to provide the necessary information to support the process planning activity. Although the MM references to Molina's work(Molina 1995) the changes introduced by the use of the STEP Application Protocols demonstrated the need to enhancements in the area of interoperable information support structures. The novel approach in representing the strategies inside the STEP-NC operations (processes capabilities) and STEP compliant resource capabilities has proved to be simpler and concise, bringing a gain from computational view point. In addition, the MM described in Chapter 7 sections 7.5 to 7.7.3 has an interoperable information structure which is generic and can be adopted by a CAPP/CAM system.

The author believes that these novelties better mimic the thinking pattern of the human being in the solution of the CAPP/CAM problems and that the information models developed in this work provide the generic supporting information relating to processes, resources and manufacturing strategies. Such models are shown to provide an effective staring point for the design of a fully compliant STEP-NC CAPP/CAM system, and to store and maintain effective part and manufacturing data.

9.6 Realisation of a STEP compliant CAPP/CAM computational prototype

It is recognised that the development and testing of a commercial CAD/CAPP/CAM system involves significant effort and will necessitate significant investment both in terms of man years and cost. This research has demonstrated a computational viewpoint through the design of STEP-TM CAPP System to represent the strategic use of a STEP compliant CAPP/CAM environment.

This system has been designed based on the author's developed STEP compliant product and manufacturing model to illustrate the major stages in process planning through to STEP-NC part programme generation. The interfaces can be used for a user validation of such a system before the system can be implemented through using a contemporary programming language such as C++ or Java. This represents a significant undertaking with clear potential commercial value for a software or machine tool vendor. Further research required to support this has been highlighted as part of the future work in section 10.3.

9.7 Case study component system demonstration

The design of an asymmetric rotational component has been adopted to demonstrate the use of the information models and interfaces of the STEP-NC CAPP turn mill environment. This component represents the typical turning and milling operations recognised by the machining industry. The application of the case study component has illustrated the ability of developing the STEP compliant system for a novel use of STEP-NC standards within a multi-process environment. However, the author recognises that the experiment should be extended to a wider range of parts in order to fully test the models.

Chapter 10

Conclusions

10.1 Introduction

The conclusions drawn from the research and case study are presented in this chapter.

10.2 Conclusions

The conclusions formulated from this research are as follows:

(i) The review and analysis of the requirements for interoperable process planning carried out in this research has highlighted the significant potential for seamless integration of CAPP/CAM offered through utilisation of STEP-NC standard.

(ii) The process planning environment described in this research shows that using ISO14649 (STEP-NC) is a strong tool to integrate together with ISO10303 (STEP), the various phases of the CAx chain and produce a seamless information flow using standardised information from the design phase (CAD) through the planning phase(CAPP/CAM) to the machining at the workstation level

(iii) STEP-NC brings forth the long awaited opportunity to empower the next generation of machine tools through the deployment of standardised geometric and manufacturing information at the machine tool. For the full adoption of such a change of paradigm shift from the traditional NC culture the major concern is the need of the user to trust the machine tool as no tool path generation is necessary in the STEP-NC program.

(iv) A set of three STEP compliant CAD/CAPP/CAM frameworks have been designed and specified to illustrate commercial and academic interpretation of the STEP-NC implemented CAD/CAM systems. The third STEP compliant framework has been demonstrated through to the development of the author's STEP compliant CAPP/CAM Turn/Mill computational view.

(v) A structured methodology for the design, specification and modelling of a STEP compliant CAPP/CAM system has been proposed and shown to be of strong potential for use as an industrial tool.

(vi) This research has shown the use of STEP-NC has substantially empowered the integration of CNC machine tools within the CAx process chain enabling interchanging of data traditionally regarded for CAD, CAPP and CAM systems to be directly interfaced with the ISO 14649 compliant machines.

(vii) The effectiveness of the product and manufacturing models as information support for STEP compliant process planning has been demonstrated. This innovation makes it possible to provide integrated support throughout the CAx process chain.

(viii) The utilisation of product and manufacturing models for the STEP compliant Turn/Mill CAPP/CAM system has been shown to be of significant advantage, through their demonstration in an asymmetric rotational component case study.

(ix) The major stages in process planning and manufacture of asymmetric rotational parts have been described and demonstrated within a STEP compliant planning and programming environment.

(x) A STEP oriented representation for a product model has been developed based on a number of various parts of ISO 10303 to enable interoperable information usage across the CAx process chain.

(xi) The strategic use of established and new STEP Application Protocols (AP 224, AP 240) and ISO 14649 has proved to be a valuable approach to enable modelling of the manufacturing model using known and standardised terminology. Thus enabling the Manufacturing Model to become a neutral structure for the integrated use of information in an industrial environment by different CAx systems provided by different vendors.

(xii) A new representation of a manufacturing model has been developed based at an operation level with process capability and constraint information to model the requirements of the turn-mill process and turn-mill manufacture resource. This was achieved using the new ISO 14649 standard to model the information regarding to the operation level.

(xiii) The performance capability of the experimental prototype reported in this thesis of a STEP compliant CAPP/CAM system shows a strong case for supporting interoperable manufacturing solutions.

(xiv) A case study of a rotational asymmetric component has been used to demonstrate the applicability of product and manufacturing model to support a STEP compliant Turn/Mill CAPP/CAM.

(xv) The prototype STEP compliant Turn/Mill CAPP/CAM system supported by product and manufacturing models, shows significant potential for the future interoperable process planning of parts for the next generation of CAPP/CAM systems to make effective use of the future ISO14649 intelligent CNC controllers.

10.3 Further work

10.3.1 Integration of AP 238 within the Manufacturing Model

The ISO 14649 Part 1 (Overview) previewed the development of the standard using ARM's and as soon as possible to provide an AIM and Application Protocols to further integrate the standard with other parts of STEP. The original concept of a STEP compliant product model and manufacturing model using AP 238 should be developed in the future to fully encompass the complete STEP standards. During the final part of this research a DIS version of the ISO 10303-238 using not only milling but also turning processes and features has been released. The author envisages that the proposed manufacturing model using AP 238 is now feasible for a Turn/Mill environment. There are also still some concerns that the AP will not be able to map fully onto the ISO 14649 standard, as required by Part 1 of ISO 14649 (Wolf 2003) This does not invalidate the manufacturing model research realised by the author, as ISO 14649 would be seen as a sub set of AP 238 and possibly used in the first conformance class for AP 238. This view of integrating AP 238 in the MM and the author's research is shown figure 10.1.

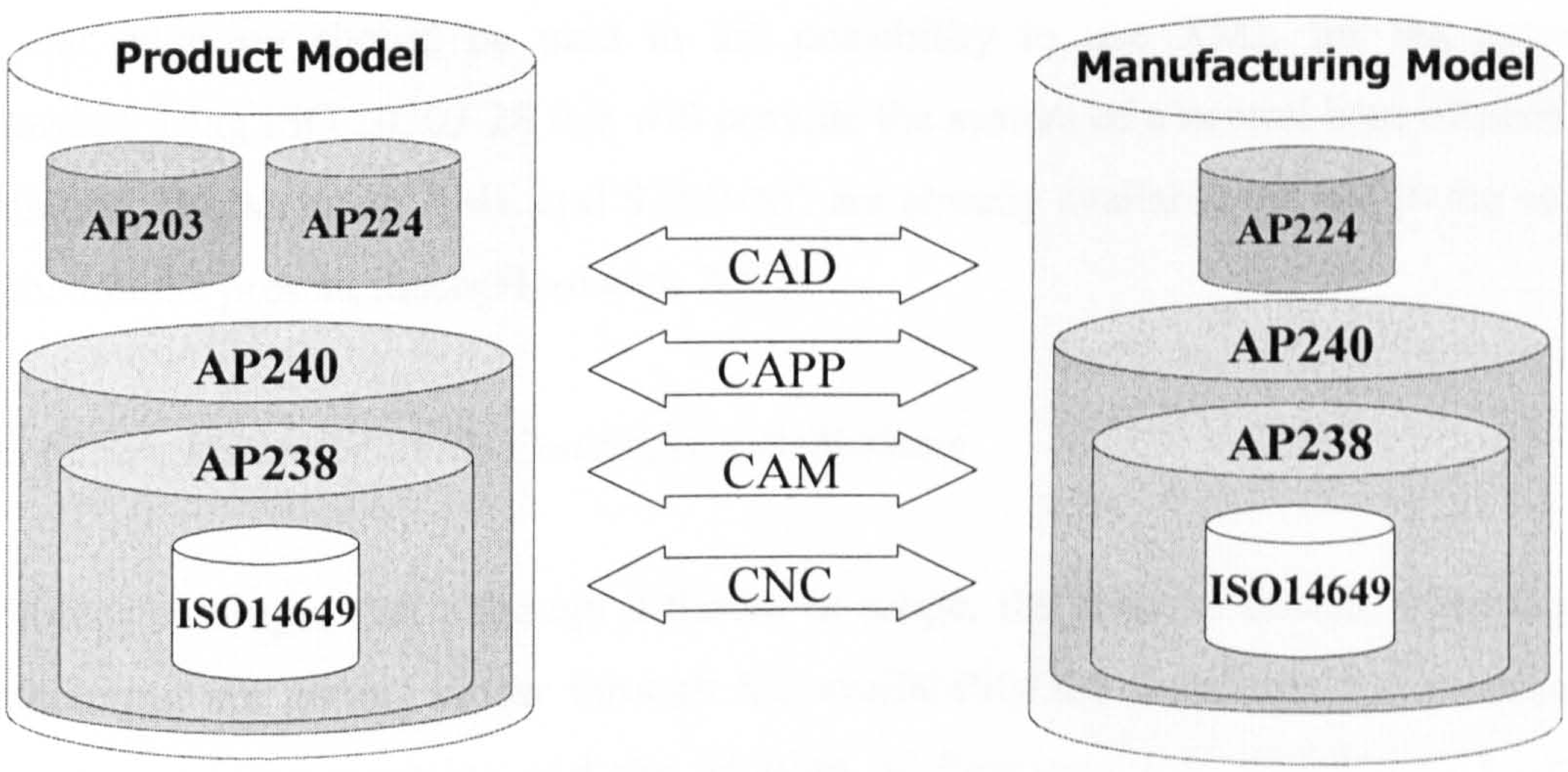


Figure 10.1 – Use of AP 238 in the Manufacturing and Product Models

10.3.2 Extend the Manufacturing Model to other technology

Further work to fully develop the Milling Machine and Fixture entities provided in the MM should be realised. The addition of processes such as on-machine inspection (using ISO 14649-16), grinding and laser hardening are also envisaged by the author. As the inspection AP 219 standard has been evolving for a number of years, the STEP-NC standard for inspection ISO 14649-16 should be a further development of the MM. The work carried out by Mr. Liaqat Ali in the Wolfson School of Mechanical and Manufacturing Engineering at Loughborough University shall provide valuable basis for this development whilst the grinding and laser processes shall be a long term project for the STEP community (Ali et al. 2005).

10.3.3 Programme implementation

Although the work has been so far developed at a modelling and conceptual level(information and computational view), the models should now be implemented using one of the object oriented languages which have already a binder in the 20's series of STEP, namely C++ and Java.

10.3.4 Implementation on a neutral persistent data/information base.

Particular attention should be paid in the possibility to use XML for the persistent information using ISO 10303-28 this will provide the system of a neutral base of persistent information. Works using XML and STEP-NC are already available but not in the context described in the present thesis(Hardwick 2004).

10.3.5 Future Vision for STEP-Compliant CAx Systems

The author envisages that although different in scope, the tasks of design, Planning and manufacturing are getting closer through the availability the Standards for Product and Manufacturing interoperability and the addition of functionalities regarded to CAPP to CAM. With the new ISO 14649 standard the possibility to merge CAM/CNC on standardised bases became a reality. The fact that STEP-NC uses product geometry, provides the possibility to have a real CAD/CAM/CNC environment using a neutral information model.

References

Ali, L.; Newman, S. T. and Petzing, J. *Development of a STEP-compliant inspection framework for discrete components*. Proceedings of the Institution of Mechanical Engineers Part B: J. Engineering Manufacture. Vol. 219. No B7, July 2005, pp 557-564.

Allada, V. and Anand, S. (1995) *Feature-based Modelling Approaches for Integrated Manufacturing: State-of-the-art Survey and Future Directions*. International Journal of Computer Integrated Manufacturing. Vol. 8(6), pp. 411-440. 1995.

Allen, R. D.; Rosso Jr., Roberto S. U.; Newman, S. T.(2002) *AB-CAM: An Intelligent Agent-Based Methodology for the Automatic Manufacture of STEP Compliant Feature Based Components*. In: Metal Cutting and High Speed MachiningEdited by Daniel Dudzinski, Alain Molinari, H. Schulz Kluwer Academic/Plenum Publishers, April/2002, pp 351-362. ISBN 0-306-46725-9

Ashworth, Martin; Bloor, M. Susan; McKay, Alison; Owen, Jon.(1996) *Adopting STEP for in-service configuration control*. Computers in industry. No 31. pp 235-253.

Bedworth, David D.; Henderson, Mark R.; Wolfe, Philip M. (1991). *Computer Integrated Design and Manufacturing*. McGraw-Hill Book Co. Singapore. Pp653. ISBN 0-07-004204-7

Bentley System Inc.(2004) http://www.bentley.com. Site Available on 30/12/2004.

Bhandarkar, Mangesh P.; Downie, Blair; Hardwick, Martin; Nagi, Rakesh. (2000) *Migrating from IGES to STEP: one to one translation of IGES drawing to STEP drafting data*. Computers in Industry. v. 41. June 2000. pp-261-277.

Bhandarkar, Mangesh P.; Nagi, Rakesh. (2000) *STEP-based feature extraction from STEP geometry for Agile Manufacturing*. Computers in Industry. v.41(1). January-2000.Pp3-24.

Bidarra, R. ; Bronsvoort, W. F. (2000) *Semantic feature modelling.* Computer-Aided Design. v 32, Issue 3. pp 201-225.March 2000.

Borja, V. -Ramirez (1997) *Redesign Supported by Data Models with Particular Reference to Reverse Engineering.* PhD Thesis. Department of Manufacturing Engineering. Loughborough University. 24/10/1997.

Boehs, Lourival. (1988) *Projeto e implantação de um sistema computadorizado de banco de dados de usinagem(CINFUS).* Doctoral Thesis (Doutorado em Engenharia Mecânica), Universidade Federal de Santa Catarina Florianópolis, 1988. (In Portuguese)

Burkett, William C. (2001*) Product Data Markup Language: a new paradigm for product data exchange and integration.* Computer Aided Design. No. 33. Pp 489-500.

CAM-I (1981) *CAM-I's Illustrated glossary of wokpiece form features.* Report R-PPP-02.1. Arlington: Computer Aided Manufacturing-International. May 1981.

Camtek Ltd.(2004). http://camtek.co.uk Site available on 23/9/2004

Case, K. (1992) *"Feature Technology - an Integration Methodology for CAD and CAM".* International Conference on Manufacturing Automation, Hong-Kong. Vol. 1, pp. 613-624. 1992.

Case, K. and Gao, J. (1993) *Feature Technology: an overview.* International Journal of Computer Integrated Manufacturing. Vol. 6, Nos. 1 & 2, pp2-12.

Case, K.; Harun, W. A. Wan.(2000) *Feature-based representation for manufacturing planning.* Int. J. Prod. Res. Vol. 38, No 17, pp 4285-4300. 2000.

Cincinnati Milacron Limited (1997). Programming Manual for Cincinnati Milacron Hawk Turning Center Model 150 with Acramatic 2100E CNC Control. Birmingham. 1997.

Costa, C. A. (2000) *Product range Models in Injection Mould Tool Design*. PhD Thesis. Department of Manufacturing Engineering. Loughborough University. 05/07/2000.

Chang, T.-C. and Wysk, R. A. (1985). *An Introduction to Automated Process Planning Systems*. New Jersey, Prentice-Hall.

Chang, T.-C.; Wysk, R. A.; Wang, Hsu-Pin (1998). *Computer-Aided Manufacturing*. Englewood Cliffs, Prentice Hall. ISBN: 013754524x

Chang, Ping-Teng and Chang, Chia-Hua. (2000) *An Integrated Artificial Intelligent Computer Aided Process Planning System*. International Journal of Computer Integrated Manufacturing. Vol 13, No 6, 483-497.

Chu, X. N.; Tso, S. K.; Tu, Y. L.(2000) *A Novel Methodology for Computer-Aided Process Planning*. Advanced Manufacturing Technology. Vol 16, pp 714-719, 2000.

Chung, J.C; Cook, R. L.; Patel, D.; Simmons, M. K. (1988) *Feature-based geometry construction for geometric reasoning*. ASME-Computers Engineering Conference. S. Fransisco. 1988.

Dassault Systems(2004). *Catia V5R13 Plm portifolio*. http://plm.3ds.com/10.0.html Site available on 23/09/2004

Delcam Plc.(2004). http://www.delcam.co.uk/ Site available on 30/12/2004

Devireddy, Chandra R. and Ghosh, Kalyan.(1999) *Feature-based modelling and neural networks-based CAPP for integrated manufacturing*. International J. Computer Integrated Manufacturing. V. 12. N. 1. Pp 61 – 74. 1999.

DPTechnology (2004) http://www.dptechnology.com Site available on 23/9/2004

Ellis, T.I.A. (1993) *Moses Project Core Document: Glossary of Terms*. Leeds University/Loughborough University. Loughborough.

ElMaraghy, Hoda A. et al. (1993) *Evolution and future perspectives in CAPP.* Annals of the CIRP. Vol. 42/2, pp 793-751.

FANUC Ltd.(1988). *Fanuc Series O-TC/OO-TC/O-MATE TC: Operator's Manual* (Senior). 1988.

Feeney, Allison Barnard; Kramer, Tom; Proctor, Fred; Hardwick Martin; Loffredo, David.(2003) *STEP-NC Implementation – ARM or AIM?*. White Paper. ISO T24 STEP-Manufacturing Meeting, S. Diego, USA, 2003-03-07

Fowler, J.(1995) *STEP for Data Management, Exchange and Sharing.* Technology Appraisals, UK. pp214, 1995.

Fowler, Martin and Scott, Kendall (2000) *UML Distilled: a brief guide to the standard object modelling language.* Addison Wesley. Boston. pp185, 2000. ISBN 0-201-65783-X

Fu, M. W.; Ong, S.K.; Lu, W.F.; Lee, I.B.H.; Nee, A.Y.C. (2003) *An approach to identify design and manufacturing features from data exchanged part model.*. Computer-Aided Design. No 35. pp979-993.

Gao, S. and Shah, J. J.(1998) *Automatic recognition of interacting machining features based on minimal condition subgraph.* Computer-Aided Design. Volume 30. No. 9. pp 727-739. August-1998.

Gindy, N. N. Z.(1989) *A hierarchical structure for form features.* Int. J. of Prod. Research. 27(12), 2089-2103. 1989.

Goldstein, Barbara L.M.; Kemmerer, Sharon J.; Parks, Curtis H.(1998). *A brief History of Early Product data Exchange Standards* – NISTR 6221. National Institute of Standards and Technology. 2/September/1998. Word Wide Web. URL, http://www.mel.nist.gov/ msidlibrary/doc/prodata.pdf Available in 20/11/2000.

Groover, Mikell P.(2001). *Automation, production systems, and computer-integrated manufacturing.* 2nd Ed. London :Prentice Hall International. 2001.

Groover, Mikell P.; Zimmers, Emory W. Jr.(1984) CAD/CAM: *Computer-Aided Design and Manufacturing.* Prentice-Hall,Inc. Englewood Cliffs. ISBN 0-13-110130-7

Guerra-Zubiaga, David Apolinar (2204). *A Manufacturing Model to Enable Knowledge Maintenance in decision Support Systems.* PhD Thesis. Wolfson School of Mechanical and Manufacturing Engineering. Loughborough University. March 2004.

Ham, I.; Lu, Stephen C. –Y. (1988). *Computer Aided Process Planning: The Present and the Future.* Annals of the CIRP 37(2): 591-601.

Han, JungHyun; Kang, Mujin; Choi, Hoogon. (2001*). STEP-based feature recognition for manufacturing cost optimization.* Computer-Aided Design. No 33, pp671-686.

Han, J. and Requicha, A. A. G. (1997) *Integration of Feature based Design and Feature Recognition.* Computer Aided Design. Vol. 29(5), pp. 393-403. 1997.

Harding, J. A. and Popplewell, K. (1996) *Driving concurrency engineering project team:a specification for an Engineering Moderator.* International Journal of Production Research. Vol. 34, No. 3, pp 841-861.

Hardwick, Martin(2004). *A Modular XML Implementation Method for STEP. White paper.* March/2004. Available in www.steptools.com.

Heusinger, S.; Rosso-Jr., R. S. U., Klemm, P.; S. T. Newman and Rahimifard, S. (2005) *Integrating the CAx Process Chain for STEP Compliant NC Manufacturing of Asymmetric Parts.* Paper accepted for publication in 2005 in the International Journal of Computer Integrated Manufacturing.

Huesinger, S. and Wosnick, M. (2003) *Data model turning: Complete machining centres.* GROWTH Project GRD1-2001-00007 "IMS/EU STEP-NC". Internal Report. May, 17th, 2003.

Hounsell, Marcelo da Silva (1998). *Feature-based Validation reasoning for Intent-driven Engineering Design*. PhD Thesis. Department of Manufacturing Engineering. Loughborough University. 27/August/1998.

Irani, S. A.; Koo, H. Y.; Raman, S. (1995) *Feature-based operation sequence generation in CAPP*. International Journal of Production Research. Vol.33. No. 1, pp 17-39. 1995.

ISG - Integrated Solutions Group / SCRA - South Carolina Research Authority.(2000a) http://isg.scra.org/products/step_ap224.html Available in 9/10/2000.

ISG - Integrated Solutions Group/SCRA - South Carolina Research Authority (2000b). http://isg.scra.org/products/slideshows/AP224_and_Mfg_Aps_LWS_012800.ppt . Available in 9/10/2000.

ISO - International Organization for Standardization (2004). Search results on 08/10/2004 on the ISO web page www.iso.ch

ISO 1832 (2004) International Organization for Standardization - ISO 1832 Indexable inserts for cutting tools -Designation. Fourth edition. 2004-06-15

ISO10303-1 (1994) International Organization for Standardization - ISO 10303-1 Industrial automation systems and integration – Product data representation and exchange. Part 1. Overview and fundamental principles. 1994.

ISO10303-11 (1994) International Organization for Standardization - ISO 10303-11 1994-12-15 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 11: Description Methods: the EXPRESS Language Reference Manual First Edition; Corrigendum 1 07/15/1999

ISO/TR 10303-12 (1997) International Organization for Standardization - ISO TR 10303-12 Industrial Automation Systems and Integration - Product Data Representation and

Exchange - Part 12: Description Methods: The EXPRESS-I Language Reference Manual First Edition, 1997-07-15

ISO10303-21 (1994) International Organization for Standardization - ISO 10303-21 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 21: Implementation Methods: Clear Text Encoding of the Exchange Structure First Edition; 1994-12-15

ISO10303-22 (1998) International Organization for Standardization - ISO 10303-22 - Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 22: Implementation Methods: Standard Data Access Interface First Edition, 1998-12-15.

ISO/TS10303-27 (2000) International Organization for Standardization – Technical Specification – ISO/TS 10303-27 -Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 27: Implementation Methods: Java™ Programming Language Binding to the Standard Data Access Interface with Internet/Intranet Extensions. 2000-11-15

ISO/TS10303-28 (2002) International Organization for Standardization – Technical Specification – ISO/TS 10303-28 -Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 28: Implementation Methods: XML Implementation of EXPRESS Schemas and Data. 2002.

ISO 10303-41 (1994) International Organization for Standardization - ISO 10303-41 1994-12-15. Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 41: Integrated Generic Resources: Fundamentals of Product Description and Support. First Edition.

ISO10303-42 (1994) International Organization for Standardization - ISO 10303-42 1994-12-15. Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 42: Integrated Generic Resources: Geometric and Topological Representation First Edition.

ISO10303-43 (1994) International Organization for Standardization - ISO 10303-43 1994-12-15. Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 43: Integrated Generic Resources: Representation Structures.

ISO10303-49 (1998) International Organization for Standartization - ISO 10303-49 1998-06-15 - Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 49: Integrated Generic Resources: Process structure and properties.

ISO10303-101 (1994) International Organization for Standardization - ISO 10303-101 1994-12-15 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 101: Integrated Application Resources: Draughting First Edition; Corrigendum 1: 04/15/1999

ISO10303-203 (1994) International Organization for Standardization - ISO 10303-203 1994-12-15 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 203: Application Protocol: Configuration Controlled Design First Edition; Technical Corrigendum 1: 03/15/1995.

ISO/CD10303-219 (2002) International Organization for Standardization – ISO/CD 10303-219 – 2002-09-08 Industrial Automation Systems and Integration - Product Data Representation and Exchange – Part 219: Application protocol: Dimensional inspection information exchange.

ISO10303-224 (2000) International Organization for Standardization - ISO 10303-224 ISO 2000-12-01 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 224: Application Protocol: Mechanical Product Definition for Process Planning Using Machining Features.

ISO10303-238 (2004) International Organization for Standardization – ISO/DIS 10303-238. Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 238: Application protocol: Application interpreted model for computerized numerical controllers. DIS (Draft International Standard). 2004-10-29.

ISO10303-240 (2003) International Organization for Standardization – ISO/DIS 10303-240. ISO Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 240: Application protocol: Process plan for machined products. 2003-10-14

ISO10303-504 (1999) International Organization for Standardization - ISO 10303-504 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 504: Application interpreted construct: Draughting annotation. 1999-03-25

ISO13399-1 (1999) International Organization for Standardization – ISO/DIS 13399-1 Cutting tool data representation and exchange - Part 1: Overview and fundamental principles. 1999.

ISO13399-2 (1999) International Organization for Standardization – ISO/DIS 13399-2 Cutting tool data representation and exchange - Part 2: Reference hierarchy for cutting tools. 1999.

ISO13399-3 (1999) International Organization for Standardization – ISO/DIS 13399-3 Cutting tool data representation and exchange - Part 3: General data for cutting tools. 1999.

ISO14649-1 (2002) International Organization for Standardization – ISO/FDIS 14649-1 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 1: Overview and fundamental principles. 2002-11-21.

ISO14649-10 (2002) International Organization for Standardization – ISO/FDIS 14649-10 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 10: General process data. 2002-11-14.

ISO14649-11 (2002) International Organization for Standardization – ISO/FDIS 14649-11 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 11: Process data for milling. 2002-11-21.

ISO14649-111 (2002) International Organization for Standardization – ISO/FDIS 14649-111 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 111: Tools for milling. 2002-11-21.

ISO14649-12 (2004) International Organization for Standardization – ISO/DIS 14649-12 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 12: Process data for turning. 2004-03-15.

ISO14649-121 (2003) International Organization for Standardization – ISO/DIS 14649-121 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 121: Tools for turning. 2003-02-28.

ISO14649-121 (2004) International Organization for Standardization – ISO/DIS 14649-121 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 121: Tools for turning. 2004-03-10.

ISO 5608 (1995) British Standard- BS4193-6 : 1997 - Hardmetal insert tooling — Part 6: Specification for the designation of turning and copying tool holders and cartridges for indexable (throwaway) inserts. Equivalent to the ISO 5608 released in 1995.

ISO6983-1 (1982) International Organization for Standardization – ISO 6983/1 – Numerical control of machines – program format and definition of address words – Part 1: Data format for positioning, line and contouring control systems. First edition, 15/09/1982.

ISO6983-2 (1988) International Organization for Standardization – ISO/DIS 6983-2 – Numerical control of machines – program format and definition of address words –

Part 2: Coding and maintenance of preparatory functions G and universal miscellaneous function M. 1988.

ISO6983-3 (1988) International Organization for Standardization – ISO/DIS 6983-3 – Numerical control of machines – program format and definition of address words – Part 3: Coding of miscellaneous functions M(classes 1 to 9). 1988.

Jain, P. K.; Kumar, Sharvan (1998). *Automatic feature extraction in PRIZCAPP.* International J. Computer Integrated Manufacturing. V. 11. N. 6. Pp 500 – 512. 1998.

Jha, Kailash; Gurumoorthy, B. (2000). *Multiple Feature Interpretation Across Domains.* Computers in Industry. v 42-1. pp. 13-32. June 2000.

Jha, K. and Gurumoorthy, B. (2000a). *Automatic propagation of feature modification across domains.* Computer-Aided Design. Volume 32, Issue 12. Pp 691-706. October 2000.

Jurrens, Kevin K.; Fowler, James E.; Algeo, Mary Elizabeth A.(1995) *Modeling of Manufacturing Resource Information, Requirements Specification*, NISTIR 5707, National Institute of Standards and Technology, Gaithersburg, MD, 1995.

Kemmerer, Sharon J.(1999). (Editor). *STEP The Grand Experience.* Manufacturing Engineering Laboratory. National Institute of Standards and Technology. Gaithersburg (MD), USA, July 1999.

Kern, Vinícius Medina(1997). *Manutenibilidade da Semântica de Modelos de Dados de Produtos Compartilhados em Rede Interoperável.*(Version in English : *Mantaining Semantics in the Integration of Network Interoperable Product*). Doctoral Thesis. Universidade Federal de Santa Catarina. Curso de Pós-Graduação em Engenhria de Produção. Florianópolis(SC). Brazil. 1997.

Kief, Hans B.; Waters, T. Frederick. (1992) *Computer Numerical Control.* Westerville (OH): Macmillan/McGraw-Hill. USA. 1992. ISBN 0—0-676411-3.

Kramer, Thomas R.(1989). *A parser that converts a boundary representation into features representation*. International Journal of Computer Integrated Manufacturing. Volume 2. No. 3. 154-163. 1989.

Kramer, Thomas R.(1991) *The Off-Line Programming System(OLPS): a prototype STEP-based NC-program generator*. NIST-USA. 1991.

Krause, F. L.; Kimura, F.; Kjelberg, T. and Lu, S.C.Y. (1993) *Product Modelling*. Annals of the CIRP. 42(2) , pp 695-705.

Kruth, Jean-Pierre; Detand, Jan; Zeir, Geert Van; Kenpenaers, Jan; Pinte, Jos.(1996) *Methods to Improve the Response Time of CAPP System that Generates non-linear Process Plans*. Advances in Engineering Software. Vol. 25. pp 9-17, 1996.

Laakko, T. and Mäntylä, M.(1993). *Feature Modelling by Incremental Feature Recognition*. Computer Aided Design. Vol. 25(8), pp. 479-492. 1993.

Lee, Wonseok; Bang, Young-Bong. (2003) *Design and Implementation of an ISO14649-Compliant CNC Milling Machine*. International Journal of Production Research. Vol.14, No. 13. pp 3007-3017.

Levin, J. B.; Dutta, D.(1992) *On the effects of parallelism on Computer-aided Process Planning*. ASME Computers in Engineering Conference. 1. 363-368. 1992.

Loffredo, David.(2000) *Fundamentals of STEP Implementation*. STEP Tolls, Inc., New York, USA. Available in Word Wide Web URL http://www.steptools.com/library/fundimpl.pdf. In 13/10/2000. Last accessed in 6/10/2004.

Liang, J; Shah, J.J.; D'Souza, R.; Urban, S.D.; Ayyaswamy; Harter, E; Bluhm, T. (1999) *Synthesis of consolidate data schema for engineering analysis from multiple STEP protocols*. Computer Aided Design (31), 429-447.

Lin, Su-Chen Jonathon(1994). *Computer Numerical Control: From Programming to Networking*. Albany: Delmar Publishers, 1994.

Liu, S. and Young, R. I. M. (2004) *Utilizing information and knowledge models to support global manufacturing co-ordination decisions*. International Journal of Computer Integrated Manufacturing, September, Vol. 17, No. 6, 479–492.

Lutz, Peter; Sperling, Wolfgang.(1997) *OSACA - the vendor neutral Control Architecture.* In: "*Facilitating Deployment of Information and Communications Technologies for Competitive Manufacturing*", Proceedings of the European Conference on Integration in Manufacturing IiM'97 Dresden/Germany, Edited by D. Fichtner, et al., Selbstverlag der TU Dresden 1997, ISBN 3-86005-192-X

Ma, S.; Maréchal, Y. Coulomb, J.-L. (2001*) Methodology for an Implementation of STEP Standard: a Java Prototype.* Advances in Engineering Software. No 32. pp 15-19.

Machinability Data Center (1980) Ed. *Machining Data Handbook.* Cincinnatti, Machinability Data Center.

Maziero, N. L.; Ferreira, J. C. E.; Pacheco, F. S.; Prim, M. F.(2000) *A feature-based object-oriented expert system to model and support product* design. J. of the Braz. Soc. of Mechanical Sciences. Vol. XXII, No 4, pp 523-543. 2000.

McKay, A.; Bloor, M.S.; De Pennington, A. (1996) *A framework for product data.* IEEE Transactions on Knowledge and Data Engineering, Vol 8, No 5, October, 1996. pp. 825-838.

McKay, A.; Bloor, M.S.; De Pennington, A. (1997) *Realising the potential of product data engineering.* 5th International Conference on Factory 2000. 2-4 April/1997. Conference publication No. 435.

MDSI - Manufacturing Data Systems, Inc (2000). *OpenCNC Architecture.* PDF document. http://www.mdsi2.com/images/DataS_Arch.pdf. Available in 17/10/2000.

Molina, Arturo -Gutierrez.(1995) *A manufacturing model to support data-driven applications for design and manufacture.* PhD Thesis. Department of Manufacturing Engineering. Loughborough University of Technology. March 1995.

Molina, A. and Bell, R. (1999) *A manufacturing model representation of a flexible manufacturing facility.* Proceedings of the Institution of Mechanical Engineers. Vol 213 Part B. pp225-246.

Molina, A. and Bell, R. (2002) *Reference models for the computer aided support of simultaneous engineering.* International Journal of Computer Integrated Manufacturing. Vol. 15, No. 3, pp 193–213

Nell, Jim. (2000). *STEP on a Page.* NIST - National Institute of Standards and Thecnology. 10/10/2000. Word Wide Web. URL http://www.mel.nist.gov/ sc5/ soap/soapword1010.pdf Available in 21/11/00.

Newman, S. T.; Allen, R. D. and Rosso Jr, R.S.U. (2003). *CAD/CAM solutions for STEP Compliant CNC Manufacture.* International Journal of Computer Integrated Manufacturing, 2003, VOL. 16, NO. 7–8, 590–597

Newman, S. T. (2004) *Integrated CAD/CAPP/CAM/CNC Manufacture for the 21st Century.* Keynote paper and Open Plenary. Proceedings of theat the International Conference in Flexible Automation and Intelligent Manufacturing (FAIM2004), Toronto, Canada. July-2004, pp 1-8. ISBN 0-662-37218-2 .

NIST- National Institute of Standards and Technology. (1993a) Draft Federal Information. Processing Standards Publication 183. Announcing the Standard for INTEGRATION DEFINITION FOR FUNCTION MODELING (IDEF0). USA. 21/December/1993.

NIST- National Institute of Standards and Technology. (1993b) Draft Federal Information. Processing Standards Publication 184. Announcing the Standard for INTEGRATION DEFINITION FOR INFORMATION MODELING (IDEF1X). USA. 21/December/1993.

OMAC-OPEN MODULAR ARCHITECTURE CONTROLS USERS GROUP (1999). *Business Justification of Open Architecture Control.* White Paper V1.0. 08/04/1999. Word Wide Web URL: http://www.arcweb.com/omac/ guidelines/BusJustV1.pdf. 07/03/2001.

Pai, P.-F. F. and E. S. Lee (2001). *Adaptive Fuzzy Systems in Group Technology.* Computers and Mathematics with Applications 42: 1393-1400.

Paris, Henri; Brissaud, Daniel.(2000) *Modelling for process planning: the links between process planning entities.* Robotics and Computer Integrated Manufacturing. Vol. 16. pp 259-266.

Pathtrace Plc.(2005) http://www.pathtrace.com . Site available on 10/08/2005.

PDES, Inc. (1997) *Concept of Operations For Application Protocol 202(DRAFT).* 13/02/1997. First Release. Word Wide Web. URL http://pdesinc.scra.org/whatsnew/reprac8.doc Available in 16/11/2000.

PDES, Inc. (1998) *Recommended Practices for AP 203.* Preliminary. April 23, 1998.

PDES, Inc. (2000) *PDES, Inc. Developed APs and Modules.* URL: http://pdesinc.scra.org/graphics/aps/213.gif . Available in 16/11/2000.

Pilot, T. and R. Knosula (1998). *The application of neural networks in group technology.* Journal of Materials Processing Technology 78: 150-155.

Prabhu, B. S.; Biswas, S. ; Pande; S. S.(2001). *Intelligente Systems for Extraction of Product Data From CADD Models.* Computers in Industry. v 44-1. pp. 79-95. January 2001.

Pratt, M. J. and P. R. Wilson(1985). *"Requirements for Support of Form Features in a Solid Modelling System".* Final Report R-85-ASPP-01. CAM-I Inc., Arlington, Texas, USA. 1985.

Proctor, Frederick M. ; Kramer, Thomas R. (1998) *A Feature-based Machining System* *using STEP*. Proceedings of SPIE - The International Society for Optical Engineering, vol.3518, 1998, pp.156-63. USA.

Proctor, F. M., Michaloski, J. L. and Shackleford, W. P. (2002) *Tying Together Design, Process Planning and Machining With STEP-NC Technology*. In: Proceedings of the Fifth Biannual World Automation Congress, February 2002, Orlando Florida USA, "Robotics, Manufacturing, Automation and Control", Vol 14, pp. 33-38, TSI Press, Albuquerque, USA.

ProSTEP Association - Association for the Advancement and Support of International Product Data Standardization-(2000) *STEP - Standardization : ISO 10303-Parts STEP Overview : Integrated Resources, APs and AICs* – URL: http://public.prostep.de/spo/ . Available in 9/12/2000.

PTC- Parametric Technology.(2004) http://www.ptc.com/ Site available on 23/9/2004

Rahimifard, S. and Newman, S. T.(1996). *A methodology to develop EXPRESS data models*. Int. J. Computer Integrated Manufacturing. 1996.Vol. 9. no. 1. pp-61-72.

Rembold, 1985, Ulrich; Blume, Christian; Dillmann, Ruediger. (1985) *Computer-integrated manufacturing technology and systems*. (Manufacturing Engineering and materials processing; 16). New York: Marcel Dekker. 1985. ISBN 0-8247-7403-5.

Rembold, U.; Nnaji, B. O.; Storr, A. (1993). *Computer Integrated Manufacturing and Engineering*. Addison-Wesley. Wokingham(UK). ISBN 0-201-56541-2

Rosso-Jr., R. S. Ubertino.(1995) *Determinação de condições otimizadas de usinagem com aplicação em torneamento*. Master Degree Dissertation (Mestrado em Engenharia Mecânica). Universidade Federal de Santa Catarina. Florianópolis, 1995. (In Portuguese).

Rosso-Jr, R. S. Ubertino. (2001) First Year Report. Loughborough University. July/2001

Rosso-Jr; Roberto S. U.; Allen R.D. and Newman, Stephen T.(2002) *Future Issues for CAD/CAM and Intelligent CNC Manufacture.* Proceedings of the 19th International Manufacturing Conference – IMC-19 Queen's University Belfast - Belfast, Northern Ireland. 28, 29 and 30/August/2002. pp115-124, ISBN: 085389-8227

Rosso-Jr, Roberto S. Ubertino and Newman, Stephen T.(2003) *Estrutura de Dados para Sistemas CAD/CAM aderente à STEP.* Livro de Actas do VI Congresso Ibero-Americano de Engenharia Mecânica. Universidade de Coimbra, Coimbra, Portugal, 15-18th October 2003, pp 1019-1024. ISBN: 972-98871-4-4

Rosso-Jr, R. S. U.; Newman, S. T. and Rahimifard, S.(2004) *The Adoption of STEP-NC for the Manufacture of Asymmetrical Rotational Components.* Proceedings of the Institution of Mechanical Engineers Part B: J. Engineering Manufacture. Vol. 218. No B11, November 2004, pp 1639-1644.

Salomons, O.W.; van Houten, F.J.A.M.; Kals, H. J. J.(1993) *Review of research in feature –based design.* Journal of Manufacturing Systems. Vol. 12, pp 113-132.

Scott, Kendal(2001). *UML Explained.* Addison-Wesley. Boston. pp 151. ISBN 0-201-72182-1

SCRA-South Carolina Research Authority (2000) RAMP project Home Page. URL http://www.ramp.scra.org/ap224_details.html . Available in 9/10/2000.

SCRA and affiliates R&D institutes.(2004) *Applying STEP to solve Real Problems.* URL: http://www.isg-scra.org/STEP/index.html Available in 26/10/2004.

Seames, Warren S.(1995) *Computer Numerical Control: concepts and programming.* Albany: Delmar Publishers. 3rd Ed. 1995.

Shah, J. J.(1991) *Assessment of Feature Technology.* Computer Aided Design. Vol. 23(5), pp. 331-343. 1991.

Shah, Jami J.; Mäntylä, Martti; Nau, Dana S.(Editors). (1994) Advances in Feature Based Manufacturing (Manufacturing research and technology). *Chapter 1.* SHAH, Jami J.; Mäntylä, Martti; Nau, Dana S. Amsterdam : Elsevier. 1994.

Shah, Jami J.; Mäntylä, Martti; Nau, Dana S.(Editors) (1994a) Advances in Feature Based Manufacturing (Manufacturing research and technology). *Chapter 6.* GADH, Rajit. Amsterdam : Elsevier. 1994.

Schenck, Douglas; Wilson, Peter (1994). *Information Modeling the EXPRESS Way.* New York: Oxford University Press. 1994. 388p.

Schenck, Douglas; Wilson, Peter (1994a). *Information Modeling the EXPRESS Way. Chapter 5: Modeling principles.* New York: Oxford University Press. 1994. 388p.

Schulz, H ; Spath, D. (1997) *Integration of Operator's Experience into NC Manufacturing.* Annals of the CIRP. Vol. 46/1. pp 415-418. 1997.

Sheu, Jinn Jong. (1998) *A computer integrated manufacturing system for rotational parts.* International J. Computer Integrated Manufacturing. V. 11. N. 6. 1998. Pp 534-547.

Shin, Hayong; Olling, Gustav; Chung, Yun C.; Kim, Bo H.; Cho, Su K. (2003) *An integrated CAPP/CAM system for stamping die pattern machining.* Computer-Aided Design. (35), 2003, pp. 203-213.

Shunmugam, M. S.; Mahesh, Puneti; Reddy, Bhaskara S.V. (2002) *A method of preliminary planning for rotational components with C-axis features using genetic algorithm.* Computers in Industry, (48) , pp. 199-217.

Sperling, Wolfgang; Lutz, Peter (1996). *Enabling Open Control Systems –An Introduction to the OSACA System Platform.* "Robotics and Manufacturing", Volume 6 - ISRAM'97 Montpellier/France,Edited by M. Jamshidi, et al., ASME Press New York 1996, ISBN 0-7918-0047-4.

Sperling, Wolfgang; Lutz, Peter (1997). *Designing Applications for an OSACA Control.* Proceedings of the International Mechanical Engineering Congress and Exposition,(The ASME Winter Annual Meeting) Dalles/USA, November 16-21, 1997

Step-NC Project (2000a). ESPRIT Project EP 29708; STEP-Compliant Data Interface for Numerical Controls (STEP-NC). *STEP-NC Newsletter. Issue 1. April/2000.* Also available in the URL: http://www.step-nc.org in 27/09/2000.

Step-NC Project (2000b) ESPRIT Project EP 29708; STEP-Compliant Data Interface for Numerical Controls (STEP-NC). *STEP-NC Newsletter. Issue 2. July/2000.* Also available in the URL: http://www.step-nc.org in 27/09/2000.

Step-NC Project (2000c) ESPRIT Project EP 29708; STEP-Compliant Data Interface for Numerical Controls (STEP-NC). *STEP-NC Newsletter. Issue 3. November/2000.* Also available in the URL: http://www.step-nc.org in 11/12/2000.

Step-NC Project (2003) EC. GROWTH project IMS STEP –NC (STEP-NC). STEP-NC Newsletter. Issue 5. September/2003. Also available in the URL: http://www.step-nc.org in 11/11/2003.

STEPTools, Inc. (2005) *StepTools Products.* Available in URL: http://www.steptools.com in 9/08/2005.

Suh, S.H.; Chung, D.H.; Lee, B.E.; Cho, J.H.; Hong, H.D.; Lee, H.S.(2002) *Developing an integrated STEP-Compliant CNC prototype.* Journal of Manufacturing Systems. Vol. 21 No. 5. pp350-362

Suh, S.H.; Lee, B.E.; Chung, D.H.; Cheon, S.U. *Architecture and implementation of a shop-floor programming system for STEP-compliant CNC.* (2003) Computer Aided Design. (35). Pp 1069-1083.

Tavakoli, Alireza -Bina (1993). *Feature Based Workshop Oriented NC Planning for Asymmetric Rotational Parts.* PhD Thesis. Department of Manufacturing Engineering. Loughborough University. March/1993.

Tseng, Yuan-Jye.(1999) *A modular modeling approach by integrating feature recognition and feature-based design.* Computers in Industry. v 39-2. pp. 113-125. June 1999.

Tseng, Yuan-Jye and Liu, Chia-Cheng.(2001) *Concurrent Analysis of Machining Sequences and Fixturing Set-up for Minimizing Set-up Changes for Mill-Turn Parts.* International Journal of Production Research. Vol 39, No. 18, pp4197-4214, 2001.

UGS PLM the Company(2004). www.ugs.com Site available on 22/09/2004.

Varvakis, G. J. -Rados (1991) *Manufacturing Code Generation for Rotational Parts in a Feature Based Product Modelling Environment.* PhD Thesis. Department of Manufacturing Engineering. Loughborough University. June/1991.

Weck, M. (2001) *Introduction to STEP-NC.* Presentation on the STEP-NC Public Seminar. 14/September/2001. Hanover Germany.

Weck, M. and Wolf, J. (2003) *A standard providing data for modern NC machining enabling enhanced functionality.* In: STEP-NC a new interface closing the gap between planning and shopfloor. WZL RWTH Aachen, STEP-NC workshop, Aachen, Germany, February 2003. Available in the URL:http://www.step-nc.org

Weck, M., Wolf, J., and Kiritis, D. (2001) *STEP-NC - The STEP compliant NC Programming Interface: Evaluation and Improvement of the Modern Interface.* In: IMS Forum, Ascona, October/2001.

Weyrich, Michael; Rommel, Bernard; Haasis, Siegmar; Müller, Peter (2000). *First Prototype of a NC Controller based on STEP-NC.* Sciences Days 2000. Available in the URL: http://www.prostep.de/ scienceday2000/DaimlerChrysler_Weirich.pdf

Williams, Dave J. (1988). *Manufacturing Systems: an introduction to technologies*. Stony Stratford: Open University Press. 1988.

Wirth, Niklaus (1977). *What Can We Do about the Unnecessary Diversity of Notation for Syntactic definitions?* Communications of the ACM. Volume 20, Number 11, November 1977.

Wolf, Jochen. (2003) *Requirements in NC machining and use cases for STEP-NC-Analysis of ISO 14649 (ARM) and AP 238 (AIM)*. White Paper. ISO T24 STEP-Manufacturing Meeting S. Diego, USA, 2003-03-07

Xu, Xun; Mao, Jim. (2004) *A STEP-Compliant Product Collaborative Development System*. In: The 33rd International Conference on Computers and Industrial Engineering, March 25-27, 2004. Jeju, Korea. CIE598

Xu, X. W.; He, Q. (2004) *Striving for total integration of CAD, CAPP, CAM and CNC*. Robotics and Computer-Integrated Manufacturing. (20). Pp 101-109.

You, Chun-Fong; Yeh, Shen-Chou (2002) *Engineering Change Propagation System using STEP*. Concurrent Engineering: Research Applications. Vol. 10. No 4. pp 349-356.

Young, R. I. M. and R. Bell.(1993) *"Design by Feature: Advantages and Limitations in Machining Planning Integration"*. International Journal of Computer Integrated Manufacturing. Vol. 6(1-2), pp. 105-112. 1993.

Young, R. I. M.(1994) *Machine Tool Programming – Techniques and Trends*. In: DORF, Richard C. and Kusiak, Andrew(Editors). *Handbook of Design, Manufacturing and Automation*. New York: John Wiley.1994.

Yamazaki Mazak Co., Ltd. (2003) *Mazatrol Fusion 640*. Publicity Material, url:http://www.mazakusa.com/, Available in 1/12/2003.

Yuen, C. F.; Venuvinod, Patri K.(1999) *Geometric feature recognition: coping with the complexity and infinite variety of features.* International J. Computer Integrated Manufacturing. V. 12. N. 5. 1998. Pp. 439-452 .

Yuen, C. F.; Wong, S. Y.; Venuvinod, Patri K.(2003) *Development of a Generic computer-aided process planning support system.* Journal of Materials Processing Technology. Vol. 139. pp394-401.

Zeid, Ibrahim.(1991) *CAD/CAM Theory and practice.* McGraw-Hill: New York. 1991.

Zha, X. F.; Du, H. (2002) *A PDES/STEP-based model and system for concurrent integrated design and assembly planning.* Computer-Aided Design. (34). Pp 1087-1110.

Zhao, J.; Cheung, W. M.; Young, R. I. M. (1999) *A consistent manufacturing data model to support virtual enterprises.* International Journal of Agile Management Systems. Vol. 1, No. 3, pp 150-158. 1999.

Appendix

Author's Research Papers

1) S. Heusinger, R. S. U. Rosso-Jr, P. Klemm, S. T. Newman and S. Rahimifard. *Integrating the CAx Process Chain for STEP Compliant NC Manufacturing of Asymmetric Parts.* Paper accepted for publication in 2005 in the International Journal of Computer Integrated Manufacturing.

2) Roberto S. U. Rosso Jr, Stephen T. Newman, Shahin Rahimifard
The Adoption of STEP-NC for the Manufacture of Asymmetric Rotational Components
Proceedings of the Institution of Mechanical Engineers Part B: J. Engineering Manufacture. Vol. 218. No B11, November 2004, pp 1639-1644.

3) Roberto S. Ubertino Rosso Jr., Stephen T. Newman
Estrutura de Dados para Sistemas CAD/CAM aderente à STEP
Livro de Actas do VI Congresso Ibero-Americano de Engenharia Mecânica
Universidade de Coimbra, Coimbra, Portugal, 15-18th October 2003, pp 1019-1024
ISBN: 972-98871-4-4

4) S.T. Newman, R. D. Allen and R.S.U. Rosso Jr
CAD/CAM solutions for STEP Compliant CNC Manufacture
Digital Enterprise Technology, P.G. Maropoulos (Ed)
Proceedings of the 1st CIRP (UK) Seminar Durham, UK, 16-17th September 2002, pp 123-128, ISBN 0-9535558-1-X , [CD-ROM].
Selected paper for the *International Journal of Computer Integrated Manufacturing*, 2003, VOL. 16, No. 7–8, pp 590–597

5) Roberto S.U. Rosso Jr; R.D. Allen and Stephen T. Newman
Future Issues for CAD/CAM and Intelligent CNC Manufacture
Proceedings of the 19th International Manufacturing Conference – IMC-19
Queen's University Belfast - Belfast, Northern Ireland.
28, 29 and 30/August/2002. pp115-124, ISBN: 085389-8227

6) R. D. Allen; Roberto S. U. Rosso Jr.; S. T. Newman
AB-CAM: An Intelligent Agent-Based Methodology for the Automatic Manufacture of STEP Compliant Feature Based Components. Third International Conference on Metal Cutting and High Speed Machining. 27, 28, 29 June 2001. Metz , France.
Selected paper published in the book Metal Cutting and High Speed Machining.
Ed: Daniel Dudzinski, Alain Molinari, H. Schulz. Kluwer Academic/Plenum Publishers, April/2002, pp 351-362. ISBN 0-306-46725-9