

**DEVELOPMENT OF A STEP FEATURE-BASED INTELLIGENT PROCESS
PLANNING SYSTEM FOR PRISMATIC PARTS**

**A THESIS SUBMITTED TO
THE GRADUTE SCHOOL OF NATURAL AND APPLIED SCIENCE
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BY

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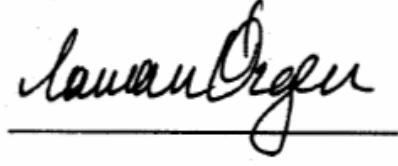
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Approval of the Graduate School of Natural and Applied Sciences



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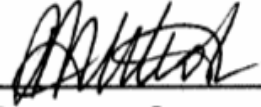

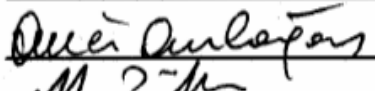


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ABSTRACT

DEVELOPMENT OF A STEP FEATURE-BASED INTELLIGENT PROCESS PLANNING SYSTEM FOR PRISMATIC PARTS

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Computer aided process planning (CAPP) is generally acknowledged as a significant activity to achieve Computer Integrated Manufacturing (CIM). In coping with the dynamic changes in the modern manufacturing environment, the awareness of developing integrated and intelligent CAPP systems has been raised in an attempt to generate more successful implementation of intelligent manufacturing systems.

The main objective of this research work has been to develop an integrated intelligent process planning system that helps designers and process planners to improve their design and planning in the early stages of the product life cycle. In order to achieve this goal, the following specific objectives have been accomplished:

- (1) Developed a STEP-based feature modeler for building mechanical parts using high-level 3D solid features as the basic design entities. The modeler is capable of generating high-level product data in XML format according to ISO 10303-AP224 standard. This file can be used to integrate into CAPP/CAM systems without using a complex feature recognition process.

- (2) Developed a STEP-based intelligent process planning system for prismatic parts. The system maps STEP AP224 XML data file and produces the corresponding machining operations to generate a digital process plan in XML format according to ISO 14649 (STEP-NC) standard. A Hybrid approach of most recent techniques of artificial intelligence (neural networks, fuzzy logic and rule-based) is used as the inference engine of the developed system.

Three neural network models are implemented to select machining operations, cutting tools, and machine tools. Several fuzzy logic models are utilized to select machining parameters for different machining operations, work material, and tool material combinations. The rule-based functions are utilized to perform operation sequence and setup planning.

An object-oriented approach has been used in the definition and implementation of the developed system. This approach offers advantages of incremental system development and reusability. The developed system is integrated with AutoCAD using Activex automation interface. Several examples have been presented to demonstrate and verify the applicability of the developed system.

Finally, this research will contribute significantly to the applicability of advanced artificial intelligent techniques in CAPP systems. The implementation of STEP technology in this research will support the integration of CAPP system with other systems in CIM environment. The developed system is intended to be an effective concurrent engineering tool that bridges the gap between design and manufacturing.

Keywords: Process Planning, CAPP, Feature-based Modeling, STEP, Product Data Modeling, STEP-NC, Fuzzy Logic, Neural Networks.

ÖZ

PRİZMATİK PARÇALAR İÇİN STEP UNSUR-TABANLI AKILLI SÜREÇ PLANLAMA SİSTEMİNİN GELİŞTİRİLMESİ

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Bilgisayarla Tümüleşik İmalat (BTİ) teknolojilerinin geliştirilmesinde Bilgisayar Destekli Süreç Proses (BDPP) genel olarak önemli bir aktivite olarak görülmektedir. Modern imalat sektöründe yer alan dinamik değışikliklere cevap verebilmek için akıllı imalat sistemlerinin daha başarılı uygulamalarının oluşturulmasında önemli bir rol oynayan tümleşik ve akıllı BDPP sistemlerinin geliştirilmesi fikri ortaya atılmıştır.

Bu çalışmanın ana amacı ürün ömür döngüsünün erken aşamalarında tasarım ve planlama çalışmalarının iyileştirilmesi için tasarımcı ve süreç planlayıcılara yardım eden tümleşik ve akıllı bir süreç planlama sisteminin geliştirilmesidir. Bu hedefe ulaşmak için, aşağıdaki spesifik amaçlara ulaşılmıştır:

- 1) Temel tasarım birimleri gibi yüksek seviyeli 3B katı unsurlar kullanılarak mekanik parçaların tasarımı için STEP-tabanlı unsur modelleyicisi geliştirilmiştir. Modelleyici yüksek seviyeli ürün verilerini ISO 10303-AP224 standartına göre XML biçiminde tutabilmektedir. Bu dosya, karmaşık unsur

tanımlayıcı süreç kullanmaksızın BDPP/BDİ sistemleriyle entegrasyonu sağlamak için kullanılır.

- 2) Prizmatik parçalar için STEP-tabanlı akıllı süreç planlama sistemi geliştirilmiştir. Sistem STEP AP224 XML veri dosyasını işler ve ISO 14649 (STEP-NC) standartına göre XML biçiminde dijital süreç planı oluşturmak için ilgili kesme işlemlerini çıkartır. Geliştirilen sistemin çıkarsama makinası gibi davranan yapay zekanın en yeni tekniklerinin (sinir ağı, bulanık mantık, kural-tabanlı) karma yaklaşımı kullanılmıştır.

Kesme operasyonlarının, kesici uçların ve takım tezgahlarının seçimi için üç tane sinir ağı modeli geliştirilmiştir. Farklı kesme operasyonları, iş parçası malzemesi, ve takım malzeme kombinasyonları için kesme parametrelerinin seçilmesi amacıyla bir çok bulanık mantık modeli uygulanmıştır. Operasyon sıralarının belirlenmesi ve kurulum planlamasının gerçekleştirilmesi için kural-tabanlı fonksiyonlardan yararlanılmıştır.

Geliştirilen sistemlerin tanımlanmasında ve uygulanmasında nesne yönelimli yaklaşım kullanılmıştır. Bu yaklaşım, artımlı sistem geliştirilmesi ve tekrar kullanım avantajlarını sunar. Geliştirilen sistemin uygulanabilirliğinin gösterimi ve doğrulanması için çeşitli örnekler verilmiştir.

Son olarak, bu araştırma BDPP sistemlerindeki ileri düzey yapay zeka tekniklerinin uygulanabilirliğine önemli ölçüde katkı sağlayacaktır. STEP teknolojisinin bu çalışmada uygulanması BDPP sisteminin BTİ ortamındaki diğer sistemlerle entegrasyonunu destekleyecektir. Geliştirilen sistem ActiveX otomasyon arayüzü kullanılarak AutCAD ile entegre edilmiştir. Geliştirilen sistem, tasarım ve üretim arasındaki bağı tamamlayacak etkili bir tümleşik mühendislik aracı olmayı amaçlamaktadır.

Anahtar Kelimeler: Süreç Planlama, BDPP, Unsur-tabanlı Modelleme, Ürün Veri Modelleme, STEP-NC, Bulanık Mantık, Sinir Ağları.

This thesis is dedicated to

My parents,

My wife, Raja,

and to

My son, Mohammed

and

My daughter, Rayan

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
AI	Artificial Intelligence
ANN	Artificial Neural Networks
B-rep	Boundary Representation
CAPP	Computer Aided Process Planning.
CAD	Computer Aided Design.
CAM	Computer Aided Manufacturing
CIM	Computer Integrated Manufacturing
CMM	Coordinates Measuring Machine
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
FBD	Feature Based Design
FL	Fuzzy Logic
FMS	Flexible Manufacturing System
GT	Group Technology
IGES	Initial Graphics Exchange Specification
ISO	International Standard Organization
NC	Numerical Control
PDM	Product Data Management
RRM	Rapid Responsive Manufacturing
STEP	Standard for Exchange of Product Data
UML	Unified Modeling Language
VB	Visual BASIC
VBA	Visual BASIC for Application
XML	Extendable Modeling Language

CHAPTER 1

INTRODUCTION

1.1 Background

In almost the last three decades, the aspect of CAPP has been dramatically changed. Although the final goal of CAPP research remains in the same direction, its contents and emphases have gone through significant changes during the time period. Many new-generation CAPP systems have been developed recently. In comparison with traditional CAPP systems, the new generation of CAPP systems has several advantages. First, artificial intelligence (AI) techniques have significantly impacted the development of CAPP systems. Although we still consider that the new generation of CAPP can be categorized into the three approaches, variant, generative, and semi-generative, AI-based CAPP systems are remarkably different from traditional generative CAPP systems. The implementation tools for the new generation systems have involved many new techniques, such as knowledge based techniques, object-oriented programming techniques, common product model, and virtual single manufacturing database techniques. In terms of the application of AI techniques in the development of CAPP, not only knowledge base and expert systems are used, but also fuzzy logic and neural network techniques have been involved. Some new generation systems have employed the machine learning approach (Zhang and Alting, 1994; Gu and Norrie, 1995).

The second difference in comparing new generation CAPP systems with traditional CAPP systems is that the integrability has been dramatically improved. In terms of the integration of design and manufacturing, the feature techniques have been recognized as essential tools for eventually integrating process planning and

design. Many researches have resulted in some applicable approaches such as feature recognition, feature-based design, etc. Many feature based process planning systems have been reported recently (Zhang and Alting, 1994; Gu and Norrie, 1995).

Generally speaking, the difference between the new generation of CAPP and traditional CAPP lies in three aspects: (1) integrability, (2) intelligence, and (3) high techniques orientation.

1.2 Overview of the Research Problem

This research work focuses on the following specific problems:

(1)The lack of standardized product data representation

The purpose of a product model is to provide a means for representing and exchanging information about a product gathered during, and used in, the design and manufacture of that product. Therefore, the contents of this product model must be able to support the information needs of a large variety of computerized manufacturing applications (i.e., CAPP, part programming, etc.). The popularity of using CAD systems as a means for creating, representing and exchanging product designs has created various standard product data exchange formats such as IGES, SET, DXF, etc. These standards have shown a success in transferring data between CAD systems, but they have failed to transfer product data from CAD to CAM applications. This is because current CAD systems are not able to support all the information concerning a part that is needed to support the CAM activities (Yang et al, 1993). One solution that offers the most promise is the creation of a standard method for representing product data that would serve the needs of all applications. The Standard for the Exchange of Product model data (STEP) is such a standard, offering the most promise as an answer to these problems (Amaitik & Kilic, 2002; An et al, 1995).

(2) The deficiency of current design approach

The product development cycle using traditional design approach can be time consuming since there is often a lack of communication between design and manufacturing engineers. There may be numerous design revisions where manufacturing engineers find that the design is too difficult or expensive to manufacture. Product development can be shortened if concurrent engineering efforts, where design and manufacturing engineers work simultaneously, are followed from the beginning. Alternatively, design engineers may be provided with a tool that can provide downstream information for their design (Chin et al, 2002). Therefore, an integrated feature-based modeler is recommended for design process improvement.

(3) Bottleneck in knowledge acquisition

Process planning is knowledge-intensive in nature. A productive CAPP (Computer Aided Process Planning) system must contain a tremendous amount of knowledge, i.e. rules about arranging machine operations and facts about the machine shop. Furthermore, the system should have flexibility because rules and facts in the database require constant updating. This is especially true in today's manufacturing environment. Expert system approach has been used to build such CAPP systems since the 1980s (Huang and Zhang, 1994). However, the results are not so promising due to the bottleneck in knowledge acquisition. New advanced artificial intelligent techniques such as neural networks and fuzzy logic provide a promising approaches for automated knowledge acquisition and can be advantageously used in the building of new generation CAPP systems (Dagli, 1994; Yue et al, 2002). This is due to their ability to acquire new knowledge and to cope with the dynamic changes of manufacturing systems.

(4) The process plan contents

The loss of product and process data that occurs when process plans are converted into much simpler formats has been the primary barrier to the introduction of intelligent control for machining. Recognition of this led to the introduction of STEP-NC (ISO 14649, and ISO 10303 AP 238) in the mid-1990s. STEP-NC is intended to be a replacement for G codes that provides much richer data and allows

feedback of process information from the machine tool back upstream to design and process planning (Jasthi, 1995; Newman et al, 2002). STEP-NC is currently being validated in pilot projects, and is showing promise as the next generation data interface to machine tools.

1.3 Research Objectives

The main objectives of this research work is to develop an integrated, STEP-based, hybrid intelligent process planning system that helps designers and process planners to improve their design and planning in the early stages of the product cycle life. In order to achieve this goal, the following specific objectives have to be accomplished:

- (1) Developing an integrated product data model for CAPP by using object-oriented modeling and product data exchange standard STEP. The main tasks of this model are: (a) to provide a standard product data model to develop CAPP systems, (b) to provide the CAPP system with the ability to integrate with other systems in CIM environment efficiently.
- (2) Developing a STEP-based feature modeler for prismatic parts. High-level 3D solid features will be used as the basic entities for the part design.
- (3) Developing a hybrid intelligent CAPP system by combining artificial neural networks, fuzzy logic, and rule-based techniques. The inference functions which will be used by the proposed CAPP system are classified into: (a) a neural networks based function which means that certain CAPP sub-functions will be performed by utilizing the neural networks based inference method, (b) the fuzzy logic inference function which will be performed by adopting the fuzzy logic inference method, and (c) The rule-based function which describes that certain CAPP sub-functions will be carried out based on set of pre-defined rules.

1.4 Organization of the Thesis

There are seven chapters in this thesis. The contents of each chapter are summarized below. Chapter 1 presents an introduction to the thesis. The sections of this chapter describe an overview of research problems, objectives, limitations, and contributions.

Chapter 2 presents a review of existing literature in related areas. The first section in this chapter presents a review to process planning and computer aided process planning (CAPP). The approaches and inference methods of CAPP are also described in this section. The next section describes a review to geometric and feature modeling techniques and presents a literature survey about feature-based design and feature-based process planning systems. The last section presents an introduction to neural networks, fuzzy logic approaches, and their applications in process planning.

Chapter 3 presents the fundamentals of STEP implementation in design and manufacturing. The first three sections in this chapter describe an introductory material to STEP development process. The next two sections describe the product data exchange mechanisms in STEP. The STEP application protocols implemented in this thesis research work are described in the last two sections as well as the implementation guidelines.

Chapter 4 deals with the steps involved in the development of STEP feature modeler (STEP-FM). The first section describes a background material. The second section presents the overall architecture of the development feature modeler. The third and fourth sections describe the base shapes and features library used by the system. The last four sections present the development processes of the feature modeler as well as the data generation mechanisms.

Chapter 5 deals with the steps involved in development of feature-based intelligent process planning system (ST-FeatCAPP). The first section describes an

introduction and purposes of the development CAPP system. The second section presents the overall structure of the ST-FeatCAPP system. The third section describes the integration of the system with CAD. The fourth section describes the application of neural networks in selection of machining operations, cutting tools, and machine tools. Designing, training, and testing the developed neural networks are also presented in this section. The fifth section describes the application of fuzzy logic in the selection of machining parameters, while the sixth section describes the application of rule-based knowledge base in the generation of setup plans. The last section describes the generation of ST-FeatCAPP system output in terms of digital process plan.

Chapter 6 describes the software development for both systems in an integrated environment. The first section in this chapter, describes the application of object-oriented modeling of the development systems. The second section presents the implementation of the software. The next section describes the installation and hardware requirements of the developed software. The last three sections in this chapter show the running procedures of both systems as well as one example for each system is presented to demonstrate the capabilities and the significance of the developed systems.

Chapter 7 summarizes the main research accomplishments of this thesis and describes the anticipated impact. This chapter is concluded by identifying directions for future research.

CHAPTER 2

LITERATURE REVIEW OF RELATED RESEARCH WORK

2.1 Process Planning

2.1.1 Introduction to process planning

Process planning can be defined as the systematic determination of the detailed methods by which workpieces or parts can be manufactured economically and competitively from initial stages (raw material form) to finished stages (desired form). Geometrical features, dimensional sizes, tolerances, materials, and surface finishes are analyzed and evaluated to determine an appropriate sequence of processing operations, which are based on specific, available machinery or workstations. In general, the inputs to process planning are design data, raw material data, facilities data (machining data, tooling data, fixture data, etc.), quality requirements data, and production type data. The output of process planning is the process plan. The process plan is often documented into a specific format and called process plan sheet. Process plan sheets may be referred to by different names, such as process sheets, operation sheets, planning sheets, route sheets, route plans or part programs. A process plan is an important document for production management. The process plan can be used for the management of production, the assurance of product quality, and the optimization of production sequencing. The process plan can even be used to determine equipment layout on the shop floor. Recent research results have also demonstrated that process planning plays an important role in a flexible manufacturing system (FMS) and computer integrated manufacturing enterprises. Process planning is the key link for integrating design and manufacturing. Because a process plan is such an important document, everyone must respect and execute it seriously. In developing a new product, the process plan provides necessary

information for technical and equipment preparation, such as tools, jigs and fixtures, machines, inspection devices, raw material stocks, inventory plans, purchasing plans, personal requirements, etc. In designing a new factory or extending or modifying an old factory, the process plan is essential information that will determine equipment requirements, area of shop floor occupation, and investment (Zhang and Alting,1994; Chang and Wysk, 1985; Gu and Norrie, 1995).

2.1.2 Computer Aided Process Planning (CAPP)

Computer Aided Process Planning (CAPP) can be defined as the functions which use computers to assist the work of process planners. The levels of assistance depend on the different strategies employed to implement the system. Lower level strategies only use computers for storage and retrieval of the data for the process plans which will be constructed manually by process planners, as well as for supplying the data which will be used in the planner's new work. In comparison with lower level strategies, higher level strategies use computers to automatically generate process plans for some workpieces of simple geometrical shapes. Sometimes process planner is required to input the data needed or to modify plans which do not fit specific production requirements well. The highest level strategy, which is the ultimate goal of CAPP, generates process plans by computer, which may replace process planners, when the knowledge and expertise of process planning and working experience have been incorporated into the computer programs. The database in a CAPP system based on the highest level strategy will be directly integrated with conjunctive systems, e.g. CAD and CAM. CAPP has been recognized as playing a key role in CIM (Zhang and Alting,1994; Chang and Wysk, 1985; Gu and Norrie, 1995).

2.1.3 Approaches of CAPP

In general, two approaches to CAPP are traditionally recognized: the variant approach and the generative approach. However, with the rapid development of new techniques, many CAPP systems do not exactly fit this classification and combine both approaches, so that a third category is now recognized, the hybrid approach. In this section these three approaches will be discussed (Zhang and Alting, 1994; Chang and Wysk, 1985; Gu and Norrie, 1995).

2.1.3.1 The variant approach

The variant approach to process planning was the first approach used to computerize the planning techniques. It is based on the concept that similar parts will have similar process plans. The computer can be used as a tool to assist in the identification of similar plans, retrieving them and editing the plans to suit the requirements for specific parts (Alting and Zhang, 1989; Donget al, 1996; Gu and Norrie, 1995).

In order to implement such a concept, part coding and classification based on group technology is used as a foundation. Individual parts are coded based upon several characteristics and attributes. Part families are created of “like” parts having sufficiently common attributes to group them into a family. This family formation is determined by analyzing the codes of the part spectrum. A “standard” plan consisting of a process plan to manufacture the entire family is created and stored for each part family. The development of a variant-process-planning system has two stages: the preparatory stage and the production stage (Figure 2.1).

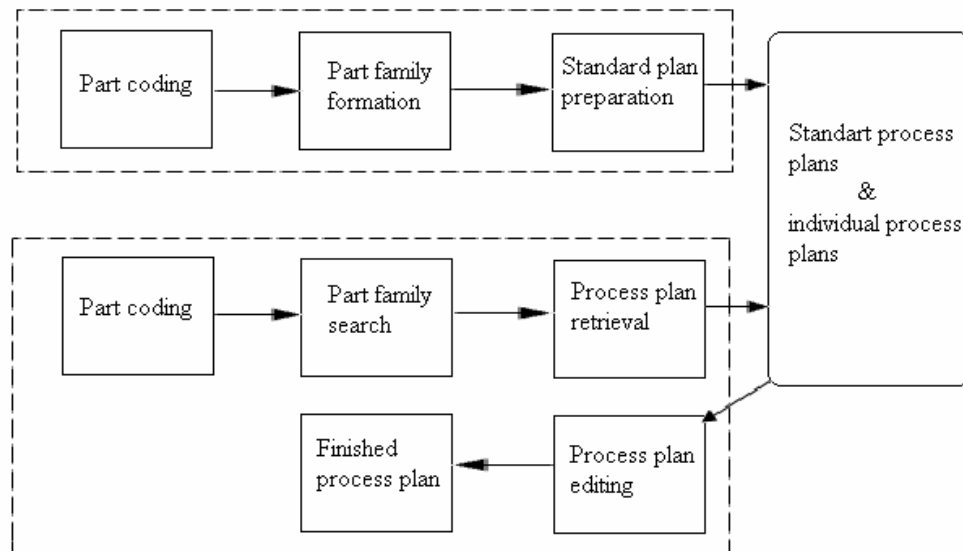


Figure 2.1 Variant process planning approach

During the preparatory stage, existing components are coded, classified, and later grouped into families. The part family formation can be performed in several ways. Families can be formed based on geometric shapes or process similarities. Several methods can be used to form these groupings. A simple approach would be to compare the similarity of the part code with other part codes. Since similar parts will have similar code characteristics, a logic which compares part of the code or the entire code can be used to determine similarity between parts.

Families can often be described by a set of family matrices. Each family has a binary matrix with a column for each digit in the code and a row for each value a code digit can have. A nonzero entry in the matrix indicates that the particular digit can have the value of that row, e.g., entry (3, 2) equals one implies that a code x3xxx can be a member of the family. Since the processes of all family members are similar, a standard plan can be assigned to the family. The standard plan is structured and stored in a coded manner using operation codes (OP-codes). An OP-code represents a series of operations on one machine/workstation. For example, an OP-code DRL10 may represent the sequence center drill, change drill, drill hole, change to reamer, and ream hole. A series of OP-codes constitute the representation of the standard process plan.

Before the system can be of any use, coding, classification, family formation, and standard plan preparation must be completed. The effectiveness and performance of the variant-process-planning system depend to a very large extent on the effort put forth at this stage. The preparatory stage is a very time-consuming process.

The production stage occurs when the system is ready for production. New components can be planned in this stage. An incoming component is first coded. The code is then sent to a part family search routine to find the family to which it belongs. Since the standard plan is indexed by family number, the standard plan can be easily retrieved from the database. The standard plan is designed for the entire family rather than for a specific component; thus, editing the plan is unavoidable (Zhang and Alting, 1994; Chang and Wysk, 1985; Gu and Norrie, 1995).

Variant-process-planning systems are relatively easy to build. However, several problems are associated with them, for example,

1. The components to be planned are limited to previously planned similar components.
2. Experienced process planners are still required to modify the standard plan for the specific component.
3. Details of the plan cannot be generated.
4. Variant planning cannot be used in an entirely automated manufacturing system, without additional process planning.

Despite these problems, the variant approach is an effective method, especially when the primary objective is to improve the current practice of process planning. In most batch-manufacturing industries, where similar components are produced repetitively, a variant system can improve the planning efficiency dramatically. Some other advantages of variant process planning are:

1. Once a standard plan has been written, a variety of components can be planned.
2. Programming and installation are comparatively simple.
3. The system is understandable, and the planner has control of the final plan.
4. It is easy to learn and easy to use.

2.1.3.2 The generative approach

Generative process planning is the second type of computer-aided process planning. It can be concisely defined as a system which automatically synthesizes a process plan for a new component. The generative approach envisions the creation of a process plan from information available in a manufacturing database without human intervention. Upon receiving the design model, the system is able to generate the required operations and operation sequence for the component (Zhang and Altng,1994; Chang and Wysk, 1985; Gu and Norrie, 1995).

Knowledge of manufacturing has to be captured and encoded into computer programs. By applying decision logic, a process planner's decision-making process can be imitated. Other planning functions, such as machine selection, tool selection, process optimization, etc., can also be automated using generative planning techniques (Roucoules et al, 2003).

A generative-process-planning system comprises three main components:

1. Part description
2. Manufacturing databases
3. Decision-making logic and algorithms

The definition of generative process planning used in industry today is somewhat relaxed. Thus, systems which contain some decision-making capability on process selection are called generative systems. Some of the so-called generative systems use a decision tree to retrieve a standard plan. Generative process planning is

regarded as more advanced than variant process planning. Ideally, a generative-process-planning system is a turnkey system with all the decision logic built in. However, due to the differences among manufacturing shops, decision logics have to be customized for each shop.

The generative-process-planning approach has the following advantages:

1. Consistent process plans can be generated rapidly.
2. New components can be planned as easily as existing components.
3. It has potential for integrating with an automated manufacturing facility to provide detailed control information.

There is no fixed representation or procedure that can be identified with generative process planning. The general trend is to use a solid model CAD-based input and expert system or an object-oriented planner construct. Most of the research systems are of this type. A few commercial products can also be classified as generative.

2.1.3.3 The hybrid approach

While fully generative process planning is the goal of CAPP system development, in the interim, systems that combine the variant and generative planning approaches are useful. We refer to these as hybrid planners. Another term used to refer to this approach is semi-generative planning (Alting and Zhang, 1989). A hybrid planner, for example, might use a variant, GT-based approach to retrieve an existing process plan, and generative techniques for modifying this plan to suit the new part (Joshi et al., 1994).

One important aspect of hybrid planning is user interaction. As generative CAPP systems become more and more automatic, the amount of work a process planner needs to do will decrease. However, this trend should not lead to a process

planning system that removes the human planner from the roles of arbitrator and editor. The human planner should always have the ability to modify and influence the CAPP system's decisions. This leads to a hybrid planning approach where two parallel planning streams exist. The first utilizes generative planning techniques, and the second a user-interaction approach. User interaction acts either to bypass generative planning functions or becomes part of feedback loops in an evaluate-and-update cycle. In this way, the user always has control over the planner and makes the final decisions when conflicts arise that cannot be resolved automatically.

2.1.4 Review of inference methods in CAPP

2.1.4.1 Traditional inference methods

The traditional inference methods for implementing the CAPP system include the variant and generative inference methods. In the variant method, the process planning inference procedure is implemented by retrieving, identifying and selecting the corresponding standard process plan of the existing parts that are identical or similar to the process plan of the new part. However, this method only allows similar process plans to be obtained for the new part. The details of the process plan, such as cutting parameters, are omitted.

The inference procedure in the generative method is implemented by using the decision-making logic and algorithms that are developed within the system software. By adopting this method, the process plan can be generated automatically without any human interaction. However, the inference procedure is limited to the predefined routes and is unchangeable, unless the CAPP system is redeveloped.

However, both the variant and generative inference methods exhibit the following deficiencies (Ming and Mak, 1999):

- 1- The inference procedure is rigid and lacks flexibility.

- 2- Only similar process plan results can be generated, in particular, those results generated from the variant inference method.
- 3- Experienced planner still needed to edit process plans.
- 4- Significant programming effort is needed.

In fact, the variant and the generative inference methods are mainly designed to handle data processing effectively for information-intensive domains. However, these two inference methods are unable to cope with the knowledge-intensive problems arising from process planning activities.

Artificial intelligence based techniques, such as expert systems, neural networks, fuzzy logic, etc., are designed to capture, represent, organize, and utilize knowledge on computers. It is therefore reasonable to use their corresponding inference methods to perform the reasoning procedure of the process planning activities (Wang, 1998; Ming and Mak, 1997; Maiyo et al, 1999; Du and Wolfe, 1997).

2.1.4.2 Expert system based inference method

In the expert system, the inference method is used to determine the starting point of the inference process, and to choose the decision rule to be executed, when several rules are available at the same time. Two main methods of inference, namely, forward and backward chaining, are used. The inference procedure in the forward chaining method is as follows: If precise clauses match the solution, then the conclusion clauses are ascertained. The backward chaining mechanism attempts to prove the hypothesis from facts. If the current goal is to determine the fact in the conclusion (hypothesis), the matching of the precise clauses to the situation has to be determined. These two methods of chaining may be combined in the expert system to induce maximum efficiency of the inference control. With reference to the forward chaining and backward chaining mechanisms in the expert system, two inference methods for the expert CAPP system, i.e. forward planning and backward planning,

are developed by using the process planning decision rules (Ming and Mak, 1999; Altung and Zhang, 1989).

Forward planning Forward planning starts the planning from the initial shape of the part, and attempts to trace the sequence of manufacturing operations towards the final shape of the finished part by employing process decision-making rules. The conditions of such rules are initial shape and the surface condition, and the actions of such rules are the manufacturing operations that remove the manufacturing features (basic matching elements) from the workpiece.

Backward planning Backward planning starts the planning from the final shape of the finished part, and attempts to trace the sequence of manufacturing operations back to the initial shape by employing process decision-making rules. The inference procedure of backward planning is thus opposite to the actual machining process, and when the workpiece begins with the final shape of the finished part, a number of machining process are carried out until the initial shape is reached.

This discussion clearly indicates that the expert system based inference method has its obvious tracing orbit, and can be explicitly retrieved again. It is therefore good at inferring with explicit knowledge, such as production rules, and is thus named the explicit inference method. Indeed, such an inference method possesses the following advantages over the traditional inference methods (Ming and Mak, 1999; Maiyo, et al, 1999):

- 1- A clear inference route and therefore the capability of the explanation facility.
- 2- The introduction of new inference rules gives flexibility in inference, thus enabling the method of adapt to the dynamic manufacturing environment to a certain extent.

Although the expert system based inference method has the above advantages, it also exhibits the following weaknesses:

- 1- Total reliance on consultation with human experts for knowledge acquisition, and thus unable to modify automatically knowledge to suit the dynamic manufacturing environment.
- 2- Inability to infer when the information provided is incomplete.

2.1.4.3 Neural networks based inference method

In view of the drawbacks of the expert system based inference method, the neural networks based inference method has been adopted in the design of intelligent CAPP systems. Neural networks belong to a format of models that are based on a learning-by-example paradigm. The inference method in neural networks performed by assigning the input data to the neural networks, and, subsequently running the neural networks by using the stored weights distributed among their neurons. The results of the outputs from neural networks are thus directly generated. This procedure indicates clearly that the inference procedure in neural networks is notably more implicit. It is quite different from the expert system based inference method, in which the inference route is explicit. In this connection, the neural networks based inference method is termed as the implicit inference method. This inference method exhibits the following advantages over the aforementioned inference methods (Ming and Mak, 1999; Maiyo, et al, 1999; Chang and Chang, 2000):

- 1- Fast inference and high working efficiency.
- 2- Its ability to perform the new inference procedure by training neural networks with new examples.
- 3- Its adaptability to the dynamic manufacturing environment, owing to efficient knowledge acquisition capability.

However, the neural networks based inference method also has the following deficiencies:

- 1- Its inability to express the inference procedure and results explicitly.

- 2- The vagueness of its knowledge representation.
- 3- The time-consuming effort to configure a neural network.

2.1.4.4 Fuzzy logic based inference method

The fuzzy system based inference method lies between expert system inference method which uses structured knowledge representation in a symbolic manner and neural network based inference method which cannot directly encode structured knowledge. The fuzzy system inference method combines the pure numerical approaches of neural networks with the structure rich approaches of expert systems. A fuzzy system inference mechanism works in three steps: (1) Fuzzification, where a crisp input is translated into a fuzzy value. (2) Rule evaluation, the fuzzy output truth values are computed. (3) Defuzzification, where the fuzzy output is translated to a crisp value (Ming and Mak, 1999; Maiyo, et al, 1999).

The advantages of this inference method are outlined as follows:

- 1- Enables approximate human reasoning in the face of uncertainty and ambiguity to be captured.
- 2- It can link between symbolic and numerical approaches in AI.

2.2 Geometric and Feature Modeling

2.2.1 Introduction to geometric modeling

Two major activities in physically realizing a product are design and manufacturing. The geometry of the product is one of the primary inputs to the design and manufacturing process. The geometric information about an object essentially includes types of surfaces and edges and their dimensions and tolerances. Traditionally, the geometric information about a part(s) has been provided on blueprints by a draftsman. Today, in an era of agile manufacturing, the emphasis is

on paperless manufacturing. That is, the geometric information should be directly transferred from Computer-Aided Design (CAD) databases to the Computer-Aided Manufacturing (CAM) databases to enable subsequent manufacture of the part. This would significantly reduce product development and manufacturing lead time. Therefore, what is needed is an efficient representation of the complete information about a design that can easily be used by subsequent applications without ambiguity. Geometric modeling refers to a set of techniques concerned mainly with developing efficient representation of geometric aspects of a design. Therefore, geometric modeling is a fundamental part of virtually all CAD tools. It is the basis of many applications such as mass property calculations, mechanism analysis, finite element modeling, and numerical control (NC) programming. Under these circumstances, geometric modeling has a tremendous influence in the process of development and manufacturing of a product(s) (Shah and Mantyla, 1995; Gu and Norrie, 1995).

Usually, there are a number of requirements for geometric modeling. The first requirement is completeness of the product representation. It means that the representation should provide enough data for users for the purpose of queries and analysis. In terms of the completeness of part representation, both topological and geometrical data are required. Informally speaking, topological data represent the relationship between entities, whereas geometric data describe the geometry of the entities. For example, for a line segment, we want to know geometric data such as the length and the orientation. We also want to know the topological data such as to which line it is connected. This type of information is important in many applications such as CAPP and NC part programming. The second requirement is that the modeling method be easy to use by designers. For example, some methods are powerful but are difficult to manipulate. The third requirement concerns the rendering capability, which means how fast the entities can be accessed and displayed by the computer. This is especially important when we model a large and complex object or in institutions involving some animation.

2.2.2 Geometric modeling techniques

There are three basic categories of geometric modeling techniques available to designers on CAD/CAM systems. These techniques are wireframe, surface, and solid modeling. The following subsections provide a basic understanding of these techniques.

2.2.2.1 Wireframe modeling

Wireframe modeling is the earliest type of geometric modeling techniques; dating back to 1960. Both 2D and 3D wireframe modeling represent objects by the edge lines, arcs, and points on the surface of the object. A wireframe modeling is same as skeletal descriptions of the product being designed. It should be noted that there are no visible surfaces on the wireframe model, only geometric entities such as lines, arcs and points. Although wireframe models do not look like a solid object, they do contain an accurate geometric description of the object being modeled. Wireframe models are practical because of the speed with which they can be displayed. Since a design workstation does not need a sophisticated color video monitor to display complex wireframe models, it is inexpensive to model objects using the 3D wireframe technique (Gu and Norrie, 1995).

2.2.2.2 Surface modeling

Surface modeling was first developed in the early 1960's. Surface modeling improves on wireframe modeling by including face information. They can model a 3D object without any ambiguity. In a surface model it can be determined whether or not a point is on the surface. When several surfaces form an object, it cannot generally be determined whether a point is inside or outside the object unless some additional information is available indicating this. The mathematical representations for surface modeling are a set of surface equations. As far as computer

representations are concerned, most of the plane surfaces can be represented or approximated using polygons. A surface model is represented in the computer by vertices, edges and faces. An advantage of surface modeling is that they are easy to construct by creating plane surfaces, as well as by sweeping, revolving, or extruding entities. Surface models are also useful for finding the intersection of surfaces in space and creating models for shaded rendering (Gu and Norrie, 1995).

2.2.2.3 Solid modeling

Solid modeling was developed in the early 1970'. Solid modeling is an unambiguous and informationally complete description of the object being represented. The construction procedure for solid modeling is different from that for wireframe and surface modeling. Instead of having to generate specific lines, arcs, and surfaces that define the object, the designer uses mathematically predefined solid primitives, such as boxes, cylinders, cones, wedges, spheres and so on. Most CAD modeling packages have a limited number of primitives available, but the designer can use them creatively to model very complex shapes. To create complex shapes, the designer can combine primitives using the Boolean operations: union (the sum of two primitives), intersection (the common mass shared by two primitives), and difference (subtracts a primitives from another). Since solid contain more information about the closure and connectivity of shapes than wireframe and surface models, they have become the most important type of model for designing, analyzing, and manufacturing products. Solid models offer a number of advantages over surface models, including the ability to calculate mass properties such as weight and center of gravity. There is several representation schemes developed and used in the solid modeling software such as constructive solid geometry (CSG), boundary representation (B-rep), primitive instancing, cell decomposition, etc. The most popular representation schemes for CAD solid modeling packages are CSG and B-rep (Gu and Norrie, 1995).

2.2.3 Deficiencies of geometric models

Geometric models have a number of deficiencies that seriously limit their usefulness to the extent that they are really attractive only for recording the detail design of the product. The following points characterize the deficiencies of conventional geometric modeling techniques in more details (Shah and Mantyla, 1995).

1. **Microscopic data** The data available in geometric models is at low, microscopic level. For instance, boundary representation models are expressed in terms of geometry (points, lines, surfaces, etc) and topology (vertices, edges, faces, etc.), and CSG in terms of solid primitives and set operations. Unfortunately, the decision-making and reasoning processes of most engineering tasks require macroscopic entities also. In general, the many types of product information needed to support engineering decision making, analysis, and reasoning for the various life cycle stages cannot be conveniently or at all included in a model consisting of microscopic entities only. For instance, tolerancing information is fundamental for manufacturing process design; yet specification of tolerances requires elements of higher level than typical geometric model entities. We can summarize this problem by saying that using geometric models leads to *underspecification*.
2. **Lack of design intent** A related problem to microscopic data is that geometric models cannot make the distinction between the geometry which is there to satisfy interface constraints, or to satisfy functional requirements, or for other reasons, such as manufacturability. To capture this type of information, a design rationale representation is required, and that generally means using a higher-level model. We can summarize this lack of information by saying that geometric models *fail to capture the design intent of the designer*.
3. **Single-level structure** Geometric models record the geometry at a single level of abstraction in terms of precisely dimensioned geometric entities. In other

words, when ordinary geometric modeling methods are used, the exact geometry of the part being designed must be known in advance and defined using exact coordinates, orientations, geometric locations, and so on. For this reason geometric models are most appropriately used after the design is completed – for documentation, not for design itself. If geometric modeling methods are used during design development, even if for only some geometric aspects of a product, a complete and formal geometric model that embodies them must be created. The inevitable result is *overspecification*: The designer is compelled to spell out a "complete" representation of the product even if there is yet no need to do so.

4. ***Tedious construction*** The geometry construction methods typically supported in geometric modelers are not in line with how designers view the part. The primitives are very low level; locating and orienting entities with respect to each other must be done tediously by means of arbitrary points, lines, and planes. Model creation in terms of low level entities not only is inefficient, but also does not support the desirability of reusing existing tested and trusted engineering solutions in design. Most engineering tasks can be characterized as variants of previous tasks where an existing basic design is modified. If the adaptation of an existing model were to be done by manipulating large quantities of low-level entities, many designers opt to create a new model from scratch.

2.4.2 Introduction to Feature Modeling

All problems of geometric modeling discussed in the previous section point in the same direction: some *macroscopic entities* should be available in explicit form in the model. The high-level modeling entities can provide the hook needed by applications to store and retrieve information. They can also be used to associate geometric and other constraints with the model in terms of high-level characteristics of the part modeled. The initial design can be synthesized quickly from the high-

level entities and their relations. More generally, the high-level entities can provide a basis for linking the design rationale with the model, hence supporting reuse of information (Case and Hounsell, 2000; Shah and Mantyla, 1995).

Feature modeling, in brief, is an approach where high-level modeling entities termed "features" are utilized to provide all the above improvements to ordinary geometric modeling techniques. This section will introduce the basic terms and concepts related to features.

2.2.5 Feature concepts

2.2.5.1 Definition of feature

Features are generic shapes with which engineers associate certain attributes and knowledge useful in reasoning about the product. Features encapsulate the engineering significance of portions of the geometry and, as such, are important in product design, product definition, and reasoning for a variety of applications. Many researchers in the past have proposed a lot of definitions for a feature and some of them are listed as follows (Hoffmann and Arinyo, 1998; Zhang and Alting, 1994):

- Codifiable properties derived from taxonomy of shapes for a particular classification scheme.
- A specific geometric configuration formed on the surface, edge, or corner of a workpiece intended to modify outward appearance or to achieve a given function.
- A characteristic volume that describes a portion of a part such as a hole, boss, pocket, etc.

Hence features designate or are related to some physical, geometric aspects of a part or assembly. They are semantically significant and distinct entities in one or more engineering viewpoints. On this basis, we can characterize a "feature" as follows (Shah et al. 1988):

- A feature is a physical constituent of a part.
- A feature is mappable to a generic shape.
- A feature has engineering significance.
- A feature has predictable properties.

A *feature model* is a data structure that represents a part or an assembly mainly in terms of its constituent features. Each feature in the feature model is an identifiable entity that has some explicit representation. The *shape* of a feature may be expressed in terms of dimension parameters and enumeration of geometric and topological entities and relations, or in terms of construction steps needed to produce the geometry corresponding to the feature. The *engineering significance* may involve formalizing the function the feature serves, or how it can be produced, or what actions must be taken when performing engineering analysis or evaluation, or how the feature "behaves" in various situations. The collection of features chosen to represent a part depends on the part type and the applications that the feature model is intended to support. New requirements are likely to lead to the introduction of new features. Nevertheless, within a chosen domain of applications, companies can choose a particular range of features that captures the geometry and the meaning of the geometry. It is precisely this customizability that makes features powerful (Shah, 1991; Bidarra and Bronsvoot, 2000).

2.2.5.2 Feature attributes

While a feature is a physical entity that makes up some physical part, an attribute (property) is a characteristic or a quality of a thing. So one can say that attributes are characteristics or properties of features, features are constituents of parts, and parts are constituents of assemblies. Attributes can be used at any level from characterizing a feature, or a collection of features, to characterizing a whole part, or an assembly. Attributes may also record characteristics of relations among features or collections of features. Assembly attributes may include such information

as mating surfaces, fits/clearances, depth of insertion, or relative orientation vectors. Part attributes may include material specifications, part number, or administrative data. Feature attributes may be position, orientation, dimensions, shape, or size tolerances. Feature-feature relation attributes may have information about relative positioning, geometric constraints, or compatibility. Entity attributes for the individual entities making up a feature could include surface finish or form tolerance (Shah and Mantyla, 1995).

2.2.5.3 Types of features

The term "feature" is used to denote modeling a wide variety of physical characteristics of parts. Therefore it is useful to distinguish between various types of features by using a sub-classification of features such as the following (Shah and Mantyla, 1995; Zhang and Alting, 1994):

- *Form features* Portions of nominal geometry; recurring, stereotypical shapes.
- *Tolerance features* Deviations from nominal form/size/location.
- *Assembly features* Grouping of various features types to define assembly relations, such as mating conditions, part relative position and orientation, various kinds of fits, and kinematic relations.
- *Functional features* Sets of features related to specific function; may include design intent, non-geometric parameters related to function, performance, etc.
- *Material features* Material composition, treatment, condition, etc.

Form features, tolerance features, and assembly features are all closely related to the geometry of parts, and are hence called collectively *geometric features*. Current feature-based CAD systems mainly address geometric features, in particular form features. This research deals mainly with form features.

Features can also be broadly classified into two main categories, as follows:

- *Explicit features* All the details of the feature are fully defined.

- *Implicit features* Sufficient information is supplied to define the feature but the full details have to be calculated when required.

2.2.5.4 Feature mapping

In developing a product, many types of design, analysis, planning, and decision-making tools and software are used. Traditionally these tasks are done sequentially. In recent years there has been increasing interest to perform these tasks concurrently in order to cut down the product development time. Regardless of the design process organization, sequential or concurrent, there is a need to share product data between various applications used during the process. A number of standards have been developed for transferring product data, such as IGES and STEP. These standards specify the format and contents of physical files that are used in exchanging product data. When dealing with features, there is a further complication: viewpoint dependence of features. How a part is viewed in terms of features varies from application to application. The design, or more appropriately, the product definition views the geometry construction units in terms of which it is convenient to define the part. The process planning views features as volumes to be removed by separate machining operations. The inspection views the paths that are to be traversed by a CMM probe and the dimensions to be gauged. Therefore the same part could be viewed as having different features, depending upon the engineering task being undertaken. This implies that feature data needs to be transformed from one viewpoint to another when exchanging product data between two dissimilar applications, such as design and manufacturing. This transformation process is referred to as *feature mapping* or *feature transformation* (Shah and Mantyla, 1995).

The major difference between feature recognition and feature mapping is in the initial state of the model from which features are derived. In feature recognition, application-specific features must be extracted directly from a geometric model. In feature mapping, application-specific features are recognized from another set of features. In theory, at least, we can say that feature mapping takes place at a higher

level because it can take advantage of features that already exist in the original feature model.

2.2.5.5 Feature data exchange

Feature-based systems are required to work with other systems and application programs. Therefore it is necessary to be able to exchange feature data between the various systems and applications. For several years now there has been an international effort in developing product data exchange standards under the STEP program. Feature data exchange is included in STEP and will be discussed in more details in the next chapter. The feature data exchange standards are likely to have a significant impact on CAD/CAM systems (Shah and Mantyla, 1995).

As far as feature data is concerned, there are two distinct purposes the exchange standard could serve: (1) to enable exchange of data between two equivalent feature modelers, for example, two design by feature systems, or (2) to transfer feature information from a feature modeler to a different application.

2.2.6 Features Creation Techniques

Many alternative techniques have been devised for creating feature-based models. We can divide them into two main categories based on whether features are extracted from geometry (FfG), or on whether geometry is created from the features (GfF). Traditionally, the FfG methods are called *feature recognition*, while GfF methods are called *design by features*. FfG may be automated by means of computer algorithms, or it may be necessary for the user to perform the task. The former is labeled *automatic feature recognition*, while the later is called *human-assisted* (or *interactive*) *feature recognition* (Shah, 1988; Shah and Mantyla, 1995; Zhang and Alting, 1994).

The procedure followed in creating feature models, in each of the above cases can be described as follows:

- *Interactive feature recognition.* A geometric model is created first, then features are created by human users, such as by picking entities in an image of the part (Figure 2.2).
- *Automatic feature recognition.* A geometric model is created first, then a computer program processes the resulting model to automatically find features (Figure 2.3).
- *Design by features.* The part geometry is created directly in terms of features; geometric models are created from the features (Figure 2.4).

Within each of these three basic approaches, there are several sub-categories. The major characteristics of each of these categories and their sub-categories are briefly discussed in the following sub-sections.

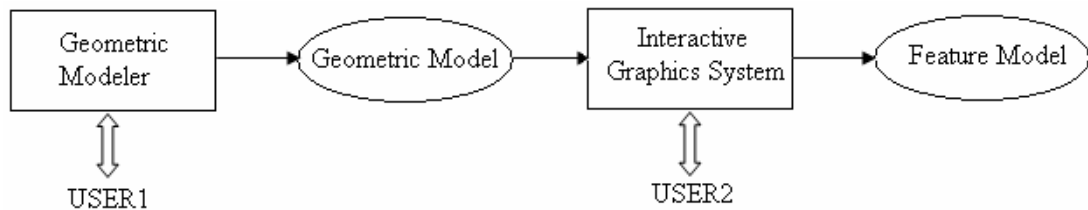


Figure 2.2 Interactive feature definition (FfG)

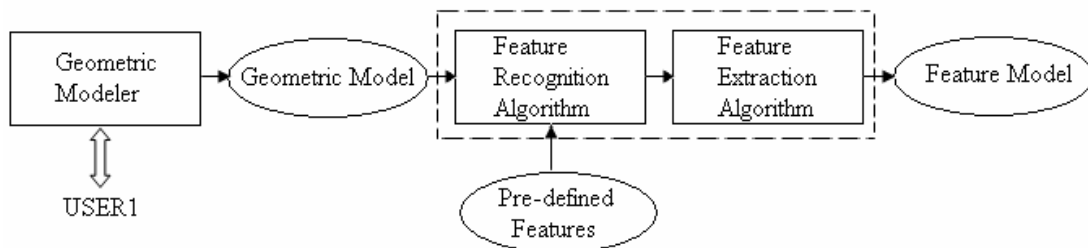


Figure 2.3 Automatic feature recognition (FfG)

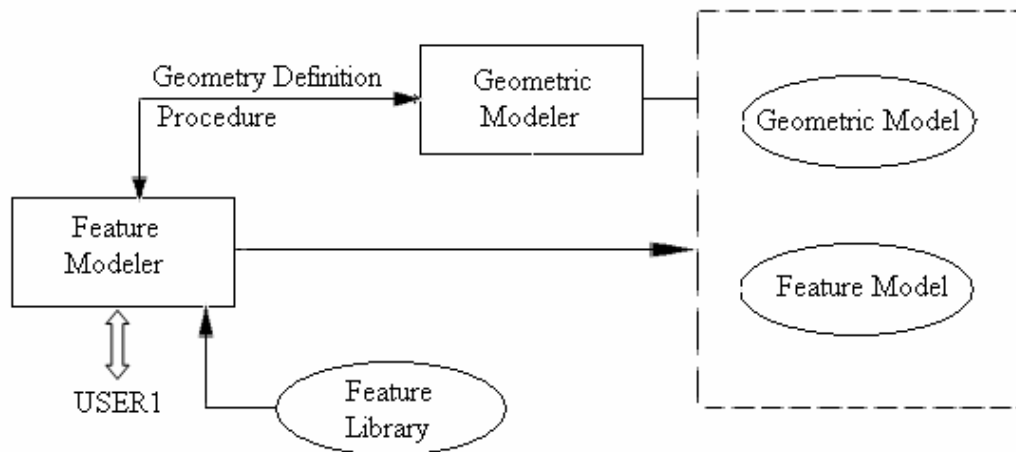


Figure 2.4 Design by features (GfF)

2.2.6.1 Interactive feature creation

Although the interactive feature recognition creation approach was originally developed to provide feature data for process planning before the availability of design by features systems, it continues to find uses because of its simplicity. In this approach the geometric model is created first, using a solid (or two-dimensional drafting type) geometric modeler. After exiting the geometric modeler, the geometric model file is sent to an interactive graphics program that renders an image of the part in order to let a user view the geometry and create features on it. The user can interactively pick entities needed to create a feature. This information is sometimes augmented with attributes such as tolerances, finish, or high-level nominal parameters (e.g. hole diameter) (Shah and Mantyla, 1995; Zhang and Alting, 1994).

2.2.6.2 Automatic feature recognition

Various techniques have been developed to provide, without any human intervention, the product data input needed by applications such as process planning, NC part programming, and inspection planning. This is popularly referred to as

feature recognition, although the output of some techniques is not in the form of features but rather as machining volumes. These latter methods typically assume that all machining will be done by milling, so it is not necessary to know the specifics of a feature other than its boundaries corresponding to final machined surfaces. For example, it does not matter if a machining volume is a rectangular pocket or an L-shaped slot because tool paths can be generated without this distinction. For this reason these methods were classified into two groups: *machining region recognition* and *pre-defined feature recognition* (Lee and Kim, 1998; Shah and Mantyla, 1995; Zhang and Alting, 1994).

2.2.6.2.1 Machining region recognition

Machining region recognition methods were devised for generating NC tool paths directly from CAD databases. The objective of these algorithms is to determine volumes that need to be removed by machining. Machining region recognition techniques may be classified into three categories (Shah and Mantyla, 1995):

- Sectioning.
- Convex hull decomposition.
- Cell decomposition.

Sectioning is typically used to generate feature boundaries corresponding to material removal regions at each z-level in 2½ D milling. The part is oriented such that its principal feature directions coincide with the three milling axes. The part volume is sliced with plans parallel to x-y plan at fixed Δz values, representing a series of tool positions. This results in one or more intersection profiles, representing the part's boundaries. These profiles are classified as "material" or "void" and offset curves are generated to form the basis for generating NC tool paths (Bobrow, 1985; Shah and Mantyla, 1995).

Convex hull decomposition is used to decompose a volume into convex machining volumes. The part is first subtracted from its convex hull, and the process is repeated until each volume is equal to its own convex hull (A convex hull of an object is the minimal convex volume that can completely enclose the object.) (Kim 1994).

Cell decomposition techniques may be thought of, in some respect, as spatial equivalents of sectioning methods. The sectioning is done along three sets of parallel planes, x-y, y-z, z-x, where x, y, z represent the machining axes of a three-axis milling machine. The x, y, z range corresponds to stock dimensions, from which the desired part is to be manufactured. The partitioning produces a lattice of cubes. The intersection of these cubes with the finished part is computed. Cells are then classified as "stock cell" or "part" cells depending on whether the intersection is closer to 0 or 1, respectively. Thus one gets a spatial decomposition model of the part; of course this step is trivial if the geometric modeler already produces such a model. Stock cells correspond to regions that need to be removed. Adjacent stock cells can be concatenated to determine tool paths. The cell sizes can be chosen to correspond to feed amounts (Woo and Sakurai, 2002).

2.2.6.2.2 Pre-defined feature recognition

Feature recognition differs from machining-region recognition in that portions of the geometric model are compared to pre-defined generic features in order to identify instances that match the pre-defined ones. Specific tasks in feature recognition may include the following:

- Searching the geometric model to match topological and geometric patterns.
- Extracting recognized features from the geometric model (i.e., removing the portion of the model associated with the recognized feature).
- Determining features parameters (hole diameter, pocket depth, etc.).
- Completing the feature geometry (edge/face growing, closure, etc.).
- Combining simple features to get higher-level features.

Both *volume-based* methods and *boundary-based* methods have been devised. Boundary-based methods find set of faces that satisfy a set of conditions for each feature. The face sets may bound a closed volume, or they may be open; the faces may contiguous or not. Volume-based methods deal only with closed volumes; all features are complete (closed), contiguous volumes.

Boundary-based methods operate primarily on boundary models and use geometric and topological relations between boundary entities to find a match for pre-defined features. For each feature, the geometric and topological conditions that need to be satisfied are identified. To find features in a solid model, the model is searched to see if the conditions corresponding to each feature are present. Volume-based methods operate directly on constructive solid models, such as CSG trees, or they produce and classify volume features from boundary models. CSG tree based recognition involves manipulation of trees to cast them in some canonical form, from which features can be recognized by matching sub-trees (Shah and Mantyla, 1995; Zhang and Alting, 1994).

2.2.6.3 Design by features

When geometric model information is available either from ordinary CAD systems or in neutral CAD data formats such as IGES or STEP, feature recognition may be the only attractive and possible method of creating features needed in manufacturing applications. On the other hand, designers might also want to take advantage of the improved environment created by features by constructing the part model directly in terms of its constituent features, and create a geometric model of the part on the basis of the features. This approach is termed *design by features*. Two methodologies for design by features are commonly used: *destructive by machining features* and *synthesis by design features*. In both methods, parts are created directly using features and geometric model is generated from the features. This requires that the design system have generic feature definitions placed in a feature library from

which features can be instanced by specifying dimensions and location parameters, the feature face on which it is to be located, and various other attributes (Wong and Wong ; Shah and Mantyla, 1995; Zhang and Alting, 1994).

2.2.6.3.1 Destructive by machining features

In the destructive by machining features approach, one starts with a model of the raw stock from which a part is to be machined; the part model is created by subtracting from the stock, features corresponding to material removed by machining operations. This facilitates a manufacturing plan to be concurrently developed. Some commercial systems support this approach. All these system use a set of pre-defined features that are subtracted from the base solid (Shah and Mantyla, 1995).

2.2.6.3.2 Synthesis by design features

The synthesis by design features approach differs from the above in that models can be built both by adding and subtracting features; it is not necessary to start with the model of the base stock. Many research and commercial systems belong to this category (Shah and Mantyla, 1995).

2.2.7 Comparison of Feature Creation Techniques

From the above discussion in the previous sub-sections it can be seen that each of the three basic feature creation methods, namely interactive creation, automatic recognition, and design by features, has some strong points and some drawbacks (Shah and Mantyla, 1995).

The interactive creation method is easy to implement. Only the features needed for an application (e.g. process planning) are identified; the entire model does not

need to be featurized. For models containing a large number of features that need to be interactively created, this method can be time-consuming. The user is responsible for feature validation, unless generic feature definitions are pre-defined to guide the user and to validate the entities picked.

The main advantage of the automatic feature recognition is that it does not impose any design constraints and performs the geometric reasoning process of the solid model. The recognition process directly extracts the low-level information from a CAD model and interprets such information as a set of well-defined features. Some important weaknesses of the automatic feature recognition approaches are mentioned. Firstly, the algorithms developed are very sophisticated and model dependent. Secondly, the type of features recognized by most approaches is very limited. Thirdly, most feature recognition approaches find it difficult to recognize compound features. Finally, feature recognition is hampered by the lack of information concerning the technological attributes (e.g. tolerances, surface finish, material specification, etc.) in the solid model's data structure.

Design-by-feature systems are already available commercially; their capabilities are rapidly growing. Design by features has the advantage that it allows designers to transfer to the model not only the features important to the part function but also their dimensioning and tolerances scheme, which encodes, to some extent, also the design intent. It further allows designers to create the part faster and more conveniently, and to make changes rapidly by taking advantage of associativity information. This richer and higher level model is available for use by downstream applications.

2.2.8 A Survey of Feature-based Design (FBD) Systems

There is much literature in the area of FBD. Many different feature definitions have been introduced and various FBD systems have been developed as stand-alone

FBD systems or implemented in the existing CAD systems. The following is a literature survey of well-known FBD systems and their characteristics.

FMDS is a feature modeling shell developed at Arizona State University in USA (Shah and Rogers, 1988). It is a system for designing, documenting and evaluating parts and is organized into a shell for product definition and another for mapping and applications. FMDS can be customized by the organization using it to define the features needed by their designers. Once the customization is complete, designers can start using FMDS to define products. FMDS consists of three separate modelers, each of which supports one type of feature. The modelers are form feature modeler, precision feature modeler, and material feature modeler. Each modeler can be used in a setup mode to create specific features and feature knowledge.

QTC is an acronym for Quick Turnaround Cell (Anderson and Chang, 1990). It utilizes the approach of destructive solid geometry. Users working on QTC should firstly instance a stock solid which is always a rectangular block. After that, users can then instance and position features on the stock. The features correspond to stock removal represented as volume that is to be subtracted by Boolean operations. FDG is an acronym for Feature-Dependency Graph, developed by Sheu and Lin at National Tsing Hua University in Taiwan (Sheu and Lin, 1993). It represents the relationships between features in the part model. Feature-position operators act as the bridges between dependent features in the FDG. Each form feature consists of a B-rep model to represent its volume, a set of abstract measure entities to support the basis for dimensioning, a set of sizes to control its intrinsic size, a set of locations for location relative to parent features, and a set of constraints to define special behavior positioning and dimensioning.

EXPO is an object-oriented feature-based design system to support concurrent design and process planning (Wong and Wong, 1995). In EXPO, a set of primitive features are built into a feature library based on the AutoCAD12 AME (Advanced Modeling Extension) geometric modeling system which is a CSG based solid modeler. AME is used to define the nominal geometry of the base stock, the

machining features, the intermediate part shapes and the finished part. In modeling a part, EXPO employs the approach of destructive modeling with features. A base stock is defined prior to feature instancing. The finished part is obtained by subtracting the machining features from the base stock. Their hierarchical boundary information such as solid, faces, edges and vertices can be obtained via boundary evaluation process. The hierarchical boundary information is then converted to the half-edge data structure.

ZD-MCADII is a product modeling system developed by Artificial Intelligent Institute of Zhejiang University in China (Hailong et al, 1996). It is a feature-based parametric modeling system integrated with CAPP/CAM systems. Feature-based modeling in ZD-MCADII allows design to include standard design elements in product geometric model and eliminates traditional, time-consuming modeling operations, and it provides various design features to facilitate the product design. ZD-MCADII also allows designer to construct his own feature libraries with user-defined feature provided by ZD-MCADII's feature module. ZD-MCADII's feature editor allows designer to modify a feature on screen by selecting the dimension and entering a new value. ZD-MCADII is able to convert design feature to manufacture feature used in CAPP and CAM by its feature mapping module.

FEBDAPP is an acronym for Feature-Based Design And Process Planning developed by Febransyah and presented in his Ph.D. dissertation at North Carolina State University (Febransyah, 2001). It is a hybrid system incorporating design by feature and feature recognition approaches. By incorporating advantages from both approaches, the system provides designers with more flexibility in creating a part than the pure design by feature approach and requires less complex feature recognition algorithms than the common feature recognition approaches. The system consists of three main subsystems as follows: (1) part creation, (2) feature mapping, and system integration. In creating a part, designers can use predefined features to build a CAD model. After the part has been created, the feature mapping process is utilized to drive all information needed for downstream applications. The CAD-

based interface developed as a part of this system integrates the system with process planning.

As revealed in the literature survey presented above, an important issue has not been dealt within the reviewed FBD systems. This issue is that no standard explicit data format representing the features has been used. Most of the FBD systems save features data in an implicit data format. In other words, these systems export features data in one file and their technological attributes in another file. These data files cannot be used directly in downstream manufacturing applications. Therefore, one of goals in this thesis is to develop new FBD system for designing mechanical parts using standard features and data format. The details of the proposed FBD system will be presented in chapter 4.

2.2.9 A Survey of Feature-based CAPP Systems

Due to the rapid development of computer techniques, the research aspects of development of CAPP systems have been changed dramatically compared with the initial research activities. Artificial intelligent techniques have been successfully introduced into CAPP systems, so that the systems can have experienced process planners' expertise for making process plans. Many generative CAPP systems have been developed, so that automated process planning concepts can be realized. While all these promising results are being carried out, the original goal of the development of CAPP still remains in the same direction – to integrate design and manufacturing. CAPP, playing a key role within CIM environment, must be integrated with design and other manufacturing functions. The systems should be open and should easily communicate with other manufacturing systems. Data structure is required to be standard and as much design and manufacturing information as possible should be processed. Recent research efforts have recognized that feature technology is an essential tool for integrating manufacturing and design. Many researches have resulted in some applicable approaches such as feature recognition, feature classification, geometrical reasoning, etc. Many feature-based CAPP systems have

been reported recently. A brief survey on the role of feature-based modeling in process planning will be presented in the following paragraphs.

Mäntylä and Opas (1988) presented an early feature-based process planning system (HutCAPP) that works on the principle of generative setup planning using a global optimization approach. Features such as grooves and slots are predefined in the system; and instances of these features present in the solid model of the part are organized into a tree. To facilitate process planning for these features, cutting directions of all features in the part are analyzed and cutting strategies are associated with these features. Essentially a cutting strategy is the access direction for the feature and the tool that can be used to generate the feature. Finally, global reasoning is applied to the cutting strategies of the various features to generate cutting plans for the whole part.

Sanii and Davis (1990) developed a framework for a feature based distributed process planning system (DiCAPP). DiCAPP uses a feature based part description system that can accept input from a number of part description technologies through IGES. DiCAPP has seven levels of recognizing the influence of the dynamic variables in manufacturing such as availability of raw materials, equipment and facilities availability work force availability, quantities to be produced and current load of production facilities. DiCAPP breaks the planning into seven levels: strategic, Preparatory, operation, setup, tooling, cut or tool path and machining parameters.

Vancza and Markus (1991) discussed the use of genetic algorithms in process planning. Parts are represented by a feature-based model. The features are used for representing and decomposing the process planning task. The process planning advances in four stages: (1) generating all potential operations for each feature, (2) generating reference features and selecting their best combination, (3) generating the precedence graph and resolving its conflicts, and (4) optimizing sequences of operations for the whole part using genetic algorithms.

Park and Khoshnevis (1993) developed a real-time computer-aided process planning system (RTCAPP) that serves as a tool for concurrent design of prismatic parts and their manufacturing processes. In RTCAPP, an interactive feature identification method is used to transform the information on part design into formalized description. RTCAPP develops the process plan incrementally as the design progresses. It employs a hierarchical planning technique, an expert system with a multi-bank rule base and a dynamic programming-based optimization module.

MCOES (Manufacturing Cell Operator's Expert System) described in (Shah and Mäntylä 1995) was developed as a design and planning system for short batch production. MCOES uses feature-based part family models for process planning. A variant feature approach is adopted so that varying levels of detail could be used in the feature model for the part families. The system consists of a design data interface, a generative process plan preparation system and an operative process planning system. The design interface supports feature-based modeling of part families. The generative planner allows manufacturing processes to be described and related to part-family models. The operative planner generates process plan and NC code based on part family descriptions.

In a system developed by Das *et al.* (1995), feature-based models (FBMs) are generated from the solid model of the part by feature recognition. Every FBM represents each feature in a single direction. The use of FBMs simultaneously with the solid model of the part allows their system to consider multiple representations of various features for both machining operation planning and automated fixture planning. In many cases a large number of these FBMs have to be evaluated to arrive at a good and feasible process plan. This is a sequential approach to process planning, in that feature recognition takes place prior to and independent of process planning.

Cherng *et al.* (1998) presented methodologies of dynamic and integrated part feature modeling and process planning for Rapid Responsive Manufacturing (RRM) applications. An integrated model of rotational part feature modeling and process

planning has been developed. The part feature modeling is constructed on the basis of a hierarchical and dynamic structure that consists of feature syntax, feature semantics and feature operations. The process planning module can fulfill both variant and generative process design tasks, and perform part manufacturability evaluation by using a multi-level knowledge reasoning.

Tseng and Lin (1999) presented feature-based tool paths for prismatic machining parts. They develop a systematic method to analyze the multiple sets of features from the machining point of view. First, the cutting tool path inside a feature and the non-cutting tool path between features are identified. Tool path generation methods are developed for different types of predefined features. As a result, a set of tool paths for machining a set of features can be determined. Finally, the multiple sets of tool paths associated with the multiple sets of features can be obtained. The multiple sets of tool paths are evaluated based on the difference in length and time. In summary, a set of features that can be machined with a shorter tool path is considered better. The parts considered in their study are three-dimensional prismatic machining parts to be machined on a three-axis NC milling or machining centre.

Devireddy and Ghosh (1999) developed a system to integrate the design and planning aspects of manufacturing, utilizing the important concepts of Feature-Based Modelling and Neural Net-works. The methodology proposed involves the development of an intelligent computer-aided process planning procedure to study the manufacturing features, and recommend manufacturing operations and their sequence. It is integrated with a Feature-Based Modeling Shell, which is used to represent the component design information.

Khoshnevis et al (1999) described the architecture of an integrated process planning system, called 3I-PP, which is comprised of three modules: feature completion, process selection, and process sequencing. They applied a knowledge-based approach to feature completion and process selection, and the space search algorithm for process sequencing. The resulting process planning system provides for

both upstream and downstream integration of CAPP with CAD and scheduling systems, respectively.

Yang et al (2001) developed a prototype feature-based multiple-alternative process planning system in which the process plan would be generated directly from design and available factory facility information. An overall removal volume is generated by graphically comparing the 3D part and 3D workpiece blank. The manufacturing features are decomposed into a series of general manufacturing features by using a mixed graph-based and rule-based algorithm. The multiple-alternative process plan generation is based on recognized manufacturing features and various production rules.

Miao et al (2002) demonstrated the use of features in automating certain process planning tasks and integrating CAD and CAM modules in commercial CAD/CAM software. Automated process planning involves two important tasks; machining feature extraction and feature-based process planning. The CAD model of the part and the stock is exported via STEP from the commercial CAD system to an external machining feature recognition system. The recognized features are used in conjunction with knowledge-based methods to prepare a process plan for the part. Set-up planning, operation sequencing and tool selection are performed automatically based on criteria such as feature shapes, feature locations, tool access directions and feasibility of workpiece locating and clamping. Features and manufacturing attributes are exported to a commercial CAM system for tool path generation and verification. A prototype system was implemented in conjunction with a commercial CAD/CAM package, SDRC/I-DEAS.

Patil and Pande (2002) developed an Intelligent Feature-based Process Planning, IFPP, for feature-based design synthesis and process planning of prismatic parts to be produced on CNC machining centers. IFPP consists of two functional modules, namely Feature Based Modeler (FBM) and Automatic process Planner (AutoPlan). The FBM provides a graphical environment for the feature-based synthesis, validation and representation of the solid model of the part to be produced. AutoPlan maps this feature information to the corresponding machining processes to

generate the operation plan and corresponding CNC code. This CNC code is unique in that it is functionally encapsulated with the feature data to provide a 'Variant' strategy utilizing the special parametric programming facilities provided on the controller. IFPP was extensively tested for several prismatic parts from industries by modeling, planning and actual machining on the CNC machining centre with a FANUC controller.

Gonzalez and Rosado (2004) developed a prototype CAPP system (GF-CAPP) aimed at obtaining the objectives of generality and standardization for CAPP at the level of processes and machines. The methodology used in GF-CAPP is based on considering the machining features as the atom of the part on which the process plan is to be constructed. Its aim, at the machine level, is to carry out the assignment of processes, operations and machines for each machining feature by using only the information with which it is associated.

As seen in the survey presented in this section, a large number of part models based on machining features have been used. Most are isolated and specific to the CAPP system using them. There have been few attempts to propose general models (Wong and Leung 2000), although individual applications usually use similar types of machining features. The STEP initiative, whose main aim is to promote information exchange, has resulted in the creation of a standard for representing machining features. The details on how STEP features can be implemented in an integrated CAD/CAPP system will be described chapters 4 and 5.

2.3 Neural Networks and Fuzzy Logic

2.3.1 Why Neural Networks

Neural network can be useful when rules are not known, either because the topic is complex or because no human expert is available. If training data can be generated, the system may be able to learn enough information to function as well as or better than an expert system. This approach also has the benefit of ease of

modification by retraining with an updated data set, thus eliminating programming changes and rule reconstruction. The data-driven aspect of neural networks allows a system adjustment as a result of changing environments and events. Another advantage of neural networks is the speed of operation after the network is trained. Neural networks can be one of the best solutions for some of the problems that have proven difficult for expert system developers, and can allow them to address problems not amenable to either approach alone. Neural networks have the potential to provide some of the human characteristics of problem solving that are difficult to simulate using the logical, analytical techniques of expert system and standard software technologies. For example, neural networks can analyze large quantities of data to establish patterns and characteristics in situations where rules are not known and can, in some cases make sense of incomplete data.

2.3.2 Introduction to Neural Networks

Artificial Neural Networks (ANNs) are biologically inspired models analogue to the basic functions of biological neurons. They have a natural propensity for storing experiential knowledge, and resemble the human brain in the sense that training rather than programming is used to acquire knowledge.

A neural network consists of a number of nodes massively interconnected through connections. The nodes are arranged in layers: an input layer, an output layer, and several hidden layers. The number of hidden layers depends on the type of problem. The nodes of the input layer receive information as input patterns, and then transform the information through the connections to the other connected nodes layer by layer to the output layer nodes. The transformation behavior of the network depends on the structure of the network and the weights of the connections [Gu & Yan, 1996]. Figure 2.5 shows a multi-layered neural network.

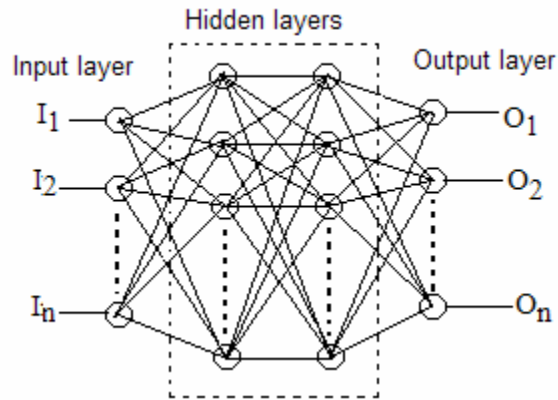


Figure 2.5 Multi-layered neural network

ANNs can be classified into unsupervised learning networks and supervised learning networks. The networks can also be classified according to the input patterns, for example binary or continuous values. In any case, a network has to go through two phases: training and application. The training of a network is done by exposing the network to a number of examples, each of them formed by an input vector and a target vector. By means of a training algorithm, the network self-learns the examples by modifying step by step the connection weights in order to reduce as much as possible the network error (difference between the output vector and the design target vector). The capability of the network to obtain a low value of the error depends on several aspects, such as: network architecture, training algorithm, initial values of weights, set of proposed examples, and number of training epochs. The learning of a new knowledge is obtained after having faced a sufficient number of times, just like a human expert does. The desired target vector is related to an input vector without explaining the reason of this relation, and the procedure of acquisition is repeated until the network has understood the mechanism of solution. However, the most relevant feature of a trained network is the capability of generating correct solutions also for new situations different from the examples proposed during the training sessions, this property of ANN is called generalization [Santochi & Dini, 1996]. This particular procedure of knowledge acquisition and the capability to face unknown situations, without having the explicit rule for solution, make ANNs an effective tool for some typical problems of process planning.

2.3.3 Application of Neural Networks in Process Planning

Process planning is knowledge intensive by the nature of the problem. A productive CAPP system must contain a tremendous amount of knowledge, i.e., rules about arranging machine operations and facts about the machine shop. Furthermore, the system should have flexibility because rules and facts in the database require constant updating. This is especially true in today's manufacturing environment. The expert system approach has been used to build such CAPP systems since 1980s. However, the results have not been promising due to the knowledge acquisition bottleneck. Neural networks offer an encouraging approach to CAPP because of their learning ability and, therefore, have great potential for application in CAPP [Mei et al, 1995]. This subsection presents a brief review of the research done for application of neural networks in CAPP.

The first attempt to use neural network techniques in process planning might be that of Osakada et al (1991). The authors applied neural network techniques to an expert system for the process planning of cold forging in order to increase the consultation speed and to provide more reliable results. A three-layer neural network is constructed to relate the shapes of rotationally symmetric products to their forming methods. The shapes of the products are transformed into 16 x 16 black and white pixels and are given to the input layer of the neural network. The back propagation algorithm is employed. After training, the network is able to determine the forming methods for the products that are exactly the same or slightly different from those used as training examples.

Hwang and Henderson (1992) applied a perceptron network in feature recognition, which is the first step in automated process planning (i.e., to interpret the design data from a CAD model). The goal of feature recognition is to convert a low level representation such as face, edge, vertex to a semantically higher feature based model. The network training is accomplished by manually presenting exemplars of features the user considers important in an engineering analysis (for example, manufacturing related features for process planning). Their result showed that neural network approach took less time in feature recognition than other traditional approaches.

Santochi and Dini (1996) applied neural networks in a particular field of CAPP systems: the selection of cutting tools. Several neural networks have been designed, each of them trained for the selection of the optimal values of a tool parameter. For each parameter a neural network has been designed, trained and validated. Training has been performed by a Backpropagation algorithm and several experiments have been carried out to identify the best architecture of the networks. The obtained results have demonstrated the applicability of neural networks for the computer aided selection of technological parameters of tools in turning.

A neural network-based CAPP approach for rotational components has been reported by Devireddy and Ghosh (1999). It makes use of a feature-based modeler to enter the machining features and their attributes via a user interactive form. Two stages of decision making are implemented in the process plan generation approach. The first stage identifies the basic machining operations needed to generate the machining features and their sequences by a neural network by taking in as input feature types and their technological attributes. The second stage deals with further refinement of the manufacturing operations into categories like roughing, semi-finishing and finishing operations by another neural network taking in as input the feature attributes and basic machining operations selected in the first stage. The process plan selection is done one feature at a time including within feature process sequencing. The network is trained with a backpropagation algorithm, using batch training. In batch training, weight adjustments are made after all the patterns are presented to the network in each iteration. The authors concluded that the use of neural networks approach has enabled the development of a very flexible CAPP methodology that can be easily trained to handle new types of components.

Mei et al (1995) presented a neural network approach for CAPP systems to automatically select manufacturing datum for rotational parts. The shape information of rotational parts is coded as basic input to the network and the tolerance specifications are also used in input as constraints. A Backpropagation algorithm is

used and several experiments are conducted. The authors concluded that the neural network has the potential to be used in CAPP systems.

Ming and Mak (2000) adopted Kohonen self-organizing neural networks and Hopfield networks to solve the setup planning problem in CAPP. Kohonen self-organizing neural networks are utilized to generate setups in terms of the constraints of fixtures/jigs, approach directions, feature precedence relationships, and tolerance relationships. The operation sequence problem and the setup sequence problem are solved by Hopfield neural networks. The authors presented a complete research basis to solve the setup planning problem in CAPP, and also developed the most efficient neural networks based approaches to solve the setup planning problem in manufacturing. Indeed, the results of the proposed approaches work towards the optimal solution to the intelligent setup planning in manufacturing.

Zuperl and Cus (2002) proposed a multi-objective optimization of cutting parameters by means of neural networks taking into consideration the technological, economical and organizational limitations. The proposed network needs three input parameters; cutting speed, feed rate and depth of cut. The output from the neural network is the manufacturer's value function. The idea of the optimization process is that the cutting parameters where the manufacturer's value function has the maximum are considered the optimum cutting parameters.

The achievements of neural networks in CAPP systems are summarized in Table 2.1. Although the capabilities are limited to discrete functions of CAPP systems, there is great potential for the application of neural networks to CAPP. The review has shown that neural network techniques can significantly improve the performance of CAPP systems. Neural networks are able to perform inference procedure with heuristic knowledge that cannot be expressed in explicit rule form. It is characterized by high processing speed through its massively interconnected, parallel architecture and adaptability to dynamic manufacturing environment owing to efficient knowledge acquisition capability. Moreover, they are robust and error tolerant and able to approximate human reasoning in the face of uncertainty.

2.3.4 Why Fuzzy Logic

In decision-support systems, the fuzzy logic approach has a distinct edge over conventional methods. Preprocessing a large range of values into a small number of fuzzy membership grades reduces the number of values that the decision-maker has to contend with to make a decision. Fewer values have to be evaluated, fewer rules are needed, and therefore in many cases a fuzzy decision support system can solve the same problem faster. In traditional decision-support modeling, the first step is to derive a mathematical model to describe the system. This requires a detailed understanding of all variables in the system and this is not always easy or possible if the system is very complicated. In contrast, fuzzy modeling deals with the relationship of the output to the input and grouping many parameters together (Berkan and Sheldon, 1997; Nguyen and Walker, 1994).

2.3.5 Introduction to Fuzzy Logic

Developed by Zadeh in 1965, fuzzy logic has been proven very successful in solving problems in many areas where conventional model based (mathematical modeling of the system) approach is either very difficult or inefficient/costly to implement. This technique can broaden the usefulness of expert systems, allowing operation in grey areas where precise values may not be known or may not be necessary for drawing conclusions. Fuzzy systems can be developed to be used alone or as parts of other software such as an expert system. They can provide a more familiar fuzzy interface to the system or allow the user to make educated guesses (Tsoukalas and Uhrig, 1997)

Table 2.1 Summary of neural networks application in process planning

Author(s)	Year	Function	Network Type	Training Method	Country
Osakada et al	1991	Cold forging	Three layer network	Backpropagation algorithm	
Hwang and Henderson	1991	Feature recognition	Perceptron	Backpropagation algorithm	USA
Knapp and Wang	1992	Machining operations selection and sequencing	Three layer network	Backpropagation algorithm	
Chen	1993	Setup generation	-	Unsupervised learning algorithm	-
Mei et al	1995	Datum selection	Multilayer perceptron network	Backpropagation algorithm	USA
Dini and Santochi	1996	Cutting tools selection	Three layer feed forward	Backpropagation algorithm	Italy
Devireddy and Ghosh	1999	Machining operations selection	Three layer feed forward	Backpropagation algorithm	Canada
Ming and Mak	2000	Setup planning	-Kohonen Self-organizing -Hopfield Network	- Unsupervised algorithm - Optimization algorithm	Hong Kong
Chang and Angkasith	2001	Machining operations sequencing	Hopfield Network	Optimization algorithm	USA
Joo et al	2001	-Machine tool selection -Cutting tools selection -cutting parameters selection	Multilayer perceptron network	Backpropagation algorithm	Korea
Ming and Mak	2001	Machining operations selection	Hopfield network	Optimization algorithm	Hong Kong
Balic and Korosee	2002	Tool path generation	Multilayer perceptron network	Backpropagation algorithm	Slovenia
Zupler and Cus	2002	Machining parameters	Multilayer perceptron network	Backpropagation algorithm	Slovenia

Fuzzy logic uses the knowledge of human experts in describing the system behavior. The fuzzy approach tries to mimic an aspect of human reasoning by doing approximate reasoning. In this way, fuzzy systems use less precise information than conventional systems but more like our everyday experience as human decision makers. The system is essentially described by a set of rules using human language with linguistic variables. Such a description of the system significantly simplifies the problem. Small, large, hot, rapidly, etc are fuzzy terms. These terms are not precise but they are meaningful and they allow us to describe our world and reason about it. Fuzzy systems allow users to give input in these imprecise terms and use them to derive precise advice. Qualitative labels, i.e. the linguistic variables, are used in expressing the system behavior using the rules, for example, "if the input increases slightly then the output decreases moderately" (Ying, 2000; Nguyen and Walker, 1994).

Fuzzy logic is a method, based on the fuzzy theory, which maps the input values to the output values. The mapping mechanism is based on some set of rules, a list of "IF-THEN" statements. Figure 2.6 shows the general case of fuzzy logic model. There are five steps in a fuzzy logic model. These steps are fuzzification of the input variables, application of the fuzzy operator "AND" or "OR", if any, in the premise, implication from the premise to the conclusion, aggregation of the conclusion across the rules and defuzzification (Berkan and Sheldon, 1997).

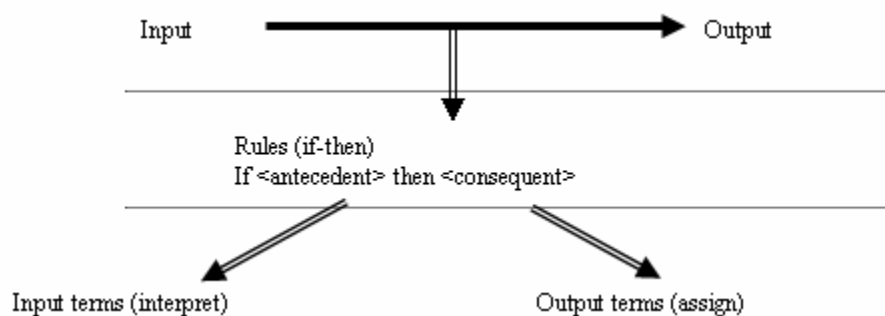


Figure 2.6 Fuzzy logic model – A general case

2.3.6 Application of Fuzzy Logic in Process Planning

Process planning is knowledge-intensive in nature. In a real manufacturing environment, the process planning problem is solved by an expert process planner based on his/her experience (heuristic) rather than accurate mathematical calculation. Although it is always desirable to model decisions mathematically, we should keep in mind that the real-life process planning problem is solved heuristically. AI-based (artificial intelligence) techniques are designed for capturing, representing, organizing, and utilizing knowledge by computers, and hence will be the key technology for automated process planning (Du and Wolfe, 1997; Zhang and Huang, 1994).

Recently, several AI techniques, including expert systems, neural networks, and fuzzy logic, have advanced to the point where they can produce promising results in solving real-life problems. The application of fuzzy logic in engineering has been focused on the area of fuzzy control. Very little literature is available in application of fuzzy logic in process planning (Singh and Mohanty, 1991). However, in process planning, some objectives are imprecise in nature. For example, an expert process planner may tell you that the criteria he/she used in process plan selection are ‘the cost should be reasonably low, the machining time should not be too long, and the final product should be acceptable in terms of quality’, etc. These objectives may not be well handled by the traditional approaches which are designed to handle deterministic information. Actually, the decision-making procedure in process planning usually involves fuzzy logic. Therefore, the application of fuzzy logic in process planning is necessary and will enhance the knowledge of the field. The use of AI techniques for automated process planning in industries is now becoming common. However, the application of fuzzy logic in process planning is somewhat overlooked (Zhang and Huang, 1994). The following is a brief survey of the literature about the application of fuzzy logic in handling different problems in automated process planning.

Zhang and Huang (1994) applied a fuzzy approach to deal with the process plan selection problem. Each process plan is evaluated and its contribution to shop floor performance is calculated using fuzzy set theory. A progressive refinement approach is used to first identify the set of process plans that maximize the contributions, and then consolidate the set to reduce the manufacturing resources needed. In most of the random examples generated, the solution yielded using their approach is identical to those obtained using other algorithms. However, their approach excels in dealing with the fuzziness of manufacturing practice. Furthermore, in some circumstances, their consolidation procedure provides more reasonable solutions than the algorithms provided by other authors.

Chen et al (1995) have developed a fuzzy expert system called Smart Assistant to Machinist, or SAM. The system consists of four modules: a database, a cutter selection module, a cutting condition design module and a learning module. The database consists of four data files: work material data file, machine tool data file, machining plan data file (which defines desirable material removal rate, surface finish, cutting speed, feed, depth of cut. etc.) and cutter data file. The cutter selection module is developed based on fuzzy logic, in which the cutter selection is conducted in three steps. First, the input information is "fuzzified". Next, using the fuzzy correlation functions, cutter grades and cutters are selected. Then, the selected grades and cutters are searched against the cutter data file to check the availability. The cutting condition design module is developed based on fuzzy non-linear programming and user interactive graphics. The learning module is developed so that users can fine-tune the fuzzy functions to further improve the performance of the system. The system has two distinct features: (1) it can select cutters and design cutting conditions based on partial and imprecise information, and (2) it selects commercial cutter products used on shop floors.

El Baradie (1995) is one of the first to suggest a fuzzy logic model for machining data selection. He described the development stages of a fuzzy logic model for metal cutting. The model is based on the assumption that the relationship between the hardness of a given material and the recommended cutting speed is an

imprecise relationship, and can be described and evaluated by the theory of fuzzy sets. The model has been applied to data extracted from the Machining Data Handbook, and a very good correlation was obtained between the handbook data and that predicted using the fuzzy logic model. The objective of the model is to facilitate the computerization process of the vast machining information contained in machining data handbooks. Also, the proposed model suggests the possibility of developing an expert system for machining data selection based on fuzzy logic.

Zhao (1995) presented an effective method that uses fuzzy sets and fuzzy decisions to create optimal process plans for metal cutting manufacture. A model of alternative process plans is proposed and fuzzy decisions are applied to the model to select optimal process plans according to certain criteria and constraints.

Wong et al (1999) have suggested a new fuzzy model for machinability data selection, which is different from El Baradie (1995). The model suggested by El Baradie (1995) was a one-input–one-output fuzzy relationship by considering the depth of cut as a discrete parameter. Whilst Wong et al. (1999) showed the feasibility of incorporating the depth of cut as one of the continuous parameters required to determine the cutting speed.

Hashmi et al (2000) have developed a fuzzy logic model used to select cutting speeds for three different materials in drilling operation. The relationship between a given material hardness and drilling speed can be described and evaluated by the fuzzy relation for different cutting tool materials and different hole diameters and feed rates. The objective of this model was to facilitate the operator to select drilling parameters from expert database which can be incorporated in computerized automated systems.

Liu (2004) has developed a fuzzy geometric programming method that can calculate the objective value when the parameters in machining optimization problem are represented as convex fuzzy numbers. A pair of two-level geometric programs is formulated to calculate the lower and upper bounds of the fuzzy

production cost at a specific α level. By enumerating the different α values, the membership function of the objective value is approximated. The derived solutions are regarded as the forward- looking information, which can be used for process planning to enhance the operational efficiency.

In this research work, a fuzzy approach to the selection of machining parameters for different types of machining operations will be proposed. The fuzzy approach is an alternative yet powerful approach to deal with machining parameters problems. It can be argued that, in order to model human expert process planners, fuzzy logic should be used in an automated process planning system. Hopefully, the idea presented in this research work will be extended to solve various tasks of process planning problems. Table 2.2 present a summary of fuzzy logic in several tasks of CAPP systems.

Table 2.2 Summary of fuzzy logic application in process planning

Author(s)	Year	Subject	Country
Zhang and Huang	1994	Process plan selection	USA
Chen et al	1995	Cutting tool selection	Canada
El baradie	1995	Machining parameters selection	Ireland
Zhao	1995	Alternative process plan	UK
Huang et al	1996	Machining operation selection	USA
Wong et al	1999	Machining parameters selection	Malaysia
Hashmi et al	2000	Machining parameters selection	UK
Shehab and Abdalla	2001	Machining cost estimation	UK
Othman et al	2002	Job Shop Scheduling	Malaysia
Hashmi et al	2003	Machining parameters selection	UK
Liu	2004	Machining parameters selection	Taiwan

CHAPTER 3

FUNDAMENTALS OF STEP IMPLEMENTATION

3.1 Introduction to STEP

STEP is an unofficial name; the actual designation of the STEP standard is *ISO10303 Industrial automation systems - Product data representation and exchange*. STEP provides a computer interpretable representation and exchange of product data. Product data represents information about a product in formal manner suitable for communication, interpretation, or processing by human beings or by computers. The objective of STEP is to provide a neutral mechanism capable of describing product data throughout the life cycle of a product independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving (Jekemmerer, 1999; Peng and Trappey, 1998).

STEP is a proactive effort, the focus being placed on developing a standard that caters for various user groups. These user groups are usually associated within an industry or according to a common application such as CAD data, which can be used throughout multiple industries. STEP is a formal standard being developed by the International Standards Organization (ISO), and is the effort to overcome the many de-facto standards that currently exist.

3.2 STEP Development Process

The need for data exchange standards was originally recognized in the late 1970s and led to the development of specifications such as the Initial Graphics

Exchange Specification (IGES) in the USA, Standard D'Exchange et de Transfert (SET) in France, and Verband der Automobilindustrie-Flachen-Schnittstelle (VDA-FS) in Germany. These standards all prescribe the use of standard file formats for the exchange of data. While the use of such national and de facto standards represented best current practice, all required considerable effort to achieve effective results. The following factors contribute to the perceived deficiencies of standards such as IGES (Jekemmerer, 1999):

- The specification is open to ambiguous interpretation, and there are therefore variations in the quality of translator software;
- Every CAD system vendor supports a subset of the standard applicable to their own products;
- The standards are limited to the exchange of geometric information (the two- or three-dimensional shapes of objects), engineering drawings, and some non-graphical data such as connectivity.

By the mid 1980s, however, it had become apparent that industry's needs would only be properly addressed by a more comprehensive international effort that would not only improve on the existing specifications, but also fulfill requirements for life-cycle product data support (Jekemmerer, 1999).

The STEP project was therefore initiated in 1984, with the following objectives.

- The creation of single international standard, covering all aspects of CAD/CAM data exchange.
- The implementation and acceptance of this standard in industry, superseding various national and de facto standards and specifications.
- The standardization of a mechanism for describing product data, throughout the life-cycle of a product, and independent of any particular system.
- The separation of the description of product data from its implementation, such that the standard would not only be suitable for neutral file exchange, but also provide the basis for shared product databases, and for long-term archiving.

It was recognized that the long-term success of STEP would be supported by identifying a minimal set of parts for fast track completion and publication. The requirements for the first release of the standard were identified in mid 1990, and much of the effort of the STEP development activity over the following four years was directed to the successful completion and publication of these parts.

The basis for the initial release was the inclusion of at least one Application Protocol, together with all necessary additional parts required to support neutral file exchange based on Application Protocols. An Application Protocol meets a specific need in specific industries and the initial release contained two such protocols; one supporting requirements for the exchange of engineering drawings, and the other supporting the exchange of configuration controlled 3D design data.

A total of twelve parts of STEP, comprising the initial release, were published by ISO early in 1995. In addition to these twelve parts, more than sixty additional parts of the standard were in development at that time. Over the ten years since its initiation, STEP has not only grown but has also altered in response to the changing needs of industry. In 1984, the key requirements were for a standard that could replace IGES, SET, VDA-FS, etc. as a more effective and efficient mechanism for the exchange of CAD/CAM data. Today, however, STEP has expanded to address industry's needs for system-independent management of product data across the full life-cycle.

STEP development is a multinational effort. At present, nineteen countries participate in the development of ISO10303 (STEP). The coordination of these efforts is accomplished through the International Standards Organization (ISO). Within ISO, there is a Technical Committee known as TC 184, which deals with Industrial Automation Systems and Integration. Further, within this technical committee there exists a sub-committee known as Subcommittee 4 (SC4) which coordinates and controls the development of the STEP standard throughout the world. The Sub Committee's title is Industrial Data.

3.3 Structure of STEP

STEP is organized as a series of parts, each published separately (Figure 3.1). These parts fall into one of the following series: description methods, integrated resources, application protocols, abstract test suites, implementation methods, and conformance testing. STEP uses a formal specification language, EXPRESS, to specify the product information to be represented. The use of a formal language enables precision and consistency of representation and facilitates development of implementations. STEP uses application protocols (APs) to specify the representation of product information for one or more applications (Jekemmerer, 1999).

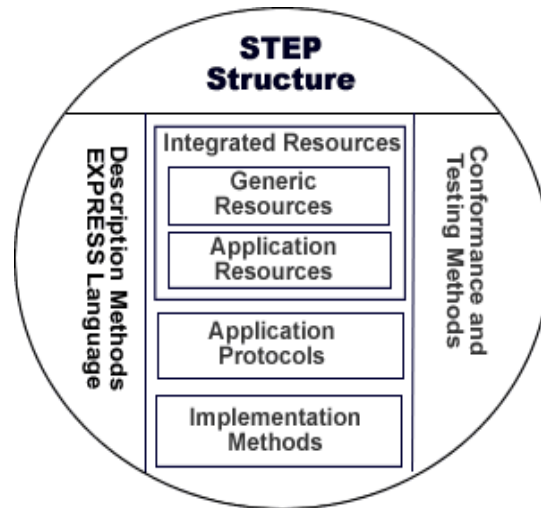


Figure 3.1 STEP Structure

The overall objective of STEP is to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving. The ultimate goal is an integrated product information database that is accessible and useful to all the resources necessary to support a product over its lifecycle. The following describes each of the structural components and functional aspects as an overview of the STEP structure (Jekemmerer, 1999)

- 0 Series: Introduction
- 10 Series: Description methods
- 20 Series: Implementation methods
- 30 Series: Conformance testing methodology and framework
- 40 Series: Integrated generic resources
- 100 Series: Integrated application resources
- 200 Series: Application protocols (APs)
- 300 Series: Abstract Test Suites
- 500 Series: Application interpreted constructs

3.3.1 Introductory documents

The **0-series** contains introductory documents describing the goal and structure of STEP. The first document of this series is ISO 10303-1 *Overview and Fundamental Principles*. It gives a general introduction to STEP and defines some basic terms.

0 Series: Introduction

- ISO 10303-1: Overview and fundamental principles

3.3.2 Description methods

The first major architectural component is the description method series of STEP parts. Description methods are common mechanisms for specifying the data constructs of STEP. Description methods include the formal data specification language developed for STEP, known as EXPRESS. Other description methods include a graphical form of EXPRESS, a form for instantiating EXPRESS models, and a mapping language for EXPRESS. The Description methods are standardized in the ISO 10303-10 series of parts.

10 Series: Description methods

- ISO 10303-11: EXPRESS language reference manual
- ISO 10303-12: EXPRESS-I language reference manual
- ISO 10303-13: Architecture and methodology reference manual
- ISO 10303-xx: EXPRESS-M language reference manual

3.3.3 Implementation methods

The second major architectural component of STEP is the implementation method series of 10303 parts. Implementation methods are standard implementation techniques for the information structures specified by the only STEP data specifications intended for implementation, application protocols. Each STEP implementation method defines the way in which the data constructs specified using STEP description methods are mapped to that implementation method. This series includes the physical file exchange structure, the standard data access interface, and its language bindings. Implementation methods are standardized in the ISO 10303-20 series of parts.

20 Series: Implementation methods

- ISO 10303-21: Clear text encoding of the exchange structure
- ISO 10303-22: Standard data access interface (SDAI)
- ISO 10303-23: C++ language binding to SDAI
- ISO 10303-24: C language binding to SDAI
- ISO 10303-25: FORTRAN language binding to SDAI
- ISO 10303-28: XML representations of EXPRESS schemas and data

3.3.4 Conformance testing

The conformance testing methodology and framework series of 10303 parts provide an explicit framework for conformance and other types of testing as an

integral part of the standard. This methodology describes how testing of implementations of various STEP parts are accomplished. The fact that the framework and methodology for conformance testing is standardized reflects the importance of testing and testability within STEP. Conformance testing methods are standardized in the ISO 10303-30 series of parts.

30 Series: Conformance testing methodology and framework

- ISO 10303-31: General Concepts
- ISO 10303-32: Requirements on testing laboratories and clients
- ISO 10303-33: Abstract test suites
- ISO 10303-34: Abstract test methods for part 21
- ISO 10303-35: Abstract test methods for part 22

3.3.5 Abstract test suites

An abstract test suite contains the set of abstract test cases necessary for conformance testing of an implementation of a STEP application protocol. Each abstract test case specifies input data to be provided to the implementation under test, along with information on how to assess the capabilities of the implementation. Abstract test suites enable the development of good processors and encourage expectations of trouble-free exchange.

300 Series: Abstract Test Suites

- ISO 10303-301: Abstract test suite: Explicit Draughting
- ISO 10303-302: Abstract test suite: Associative Draughting
- ISO 10303-303: Abstract test suite: Configuration Controlled Design
- ISO 10303-304: Abstract test suite: Mechanical Design using boundary
- ISO 10303-305: Abstract test suite: Mechanical design using surface representation
- ISO 10303-307: Abstract test suite: Sheet metal die planning and design
- ISO 10303-308: Abstract test suite: Life cycle product change process

3.3.6 Application protocols

Application protocols (APs) are the implementable data specifications of STEP. APs include an EXPRESS information model that satisfies the specific product data needs of a given application context. APs may be implemented using one or more of the implementation methods. They are the central component of the STEP architecture, and the STEP architecture is designed primarily to support and facilitate developing APs. Many of the components of an application protocol are intended to document the application domain in application-specific terminology. This facilitates the review of the application protocol by domain experts.

200 Series: Application protocols (APs)

- ISO 10303-201: Explicit Draughting
- ISO 10303-202: Associative Draughting
- ISO 10303-203: Configuration controlled design
- ISO 10303-204: Mechanical design using boundary representation
- ISO 10303-205: Mechanical design using surface representation
- ISO 10303-206: Mechanical design using wireframe representation
- ISO 10303-207: Sheet metal die planning and design
- ISO 10303-208: Life cycle product change process
- ISO 10303-209: Design-analysis of composite structures
- ISO 10303-210: Printed circuit assembly product design data
- ISO 10303-211: Electronic test, diagnostics and remanufacture
- ISO 10303-212: Electrotechnical design and installation
- ISO 10303-213: Numerical control process plans for machined parts
- ISO 10303-214: Core data for automotive mechanical design processes
- ISO 10303-215: Ship arrangements
- ISO 10303-216: Ship moulded forms
- ISO 10303-217: Ship piping
- ISO 10303-218: Ship structures
- ISO 10303-219: Dimensional inspection process planning

- ISO 10303-220: Printed circuit assembly manufacturing planning
- ISO 10303-221: Functional data and schematic representations for process plants
- ISO 10303-222: Design-manufacturing for composite structures
- ISO 10303-223: Exchange of design and manufacturing information for cast parts
- ISO 10303-224: Mechanical product definition for process planning using form
- ISO 10303-226: Ship mechanical systems
- ISO 10303-227: Plant spatial configuration
- ISO 10303-228: Building services: Heating, ventilation and air condition
- ISO 10303-230: Building structural frame: Steelwork

3.3.7 Integrated resources

The generic resources contained in the 40 series (*Integrated resources: Generic resources*) define the application-independent information models. Together with the 100 series (*Integrated resources: Application resources*) they build the so-called integrated product model.

40 Series: Integrated generic resources

- ISO 10303-41: Fundamentals of product description and support
- ISO 10303-42: Geometric and topological representation
- ISO 10303-43: Representation structures
- ISO 10303-44: Product structure configuration
- ISO 10303-45: Materials
- ISO 10303-46: Visual Presentation
- ISO 10303-47: Shape variation tolerance
- ISO 10303-48: Form features
- ISO 10303-49: Process structure and properties

3.3.8 Application interpreted constructs

Application interpreted constructs are data specifications that satisfy a specific product data need that arises in more than one application context. An application interpreted construct specifies the data structures and semantics that are used to exchange product data common to two or more application protocols.

500 Series: Application interpreted constructs

- ISO 10303-502: Topology bounded surface and Breps
- ISO 10303-506: Draughting elements
- ISO 10303-507: Geometrically bounded surface
- ISO 10303-509: Manifold surface
- ISO 10303-510: Geometrically bounded wireframe
- ISO 10303-512: Faceted Brep
- ISO 10303-513: Elementary Brep
- ISO 10303-514: Advanced Brep
- ISO 10303-515: Constructive solid geometry
- ISO 10303-516: Mechanical design context

3.4 Product Data Representation in STEP

Representation of product data elements can become quite complex, making them difficult to define and understand. The most important criterion for the product data representation used in STEP is that they must be unambiguous. This prevents their being misinterpreted by applications, or being interpreted differently by different applications (Carver and Bloom, 1991). The developers of STEP employ information modeling techniques to ensure that STEP will be unambiguous. STEP uses the EXPRESS language as a tool to represent product data in object-oriented and integrated environment. The syntax and related information of EXPRESS are described in ISO 10303-11. EXPRESS is an object-oriented data descriptive language which classifies and constructs product data in terms of entities. EXPRESS

enables precision and consistency of product data representation and facilitates implementation. Each element of the product data has an EXPRESS representation format which describes the parameters associated in the definition of that element. For Example, in the part shape representation model, the cylindrical base shape can be represented in EXPRESS format as follows;

```
ENTITY block_base_shape
  SUBTYPE OF (implicit_base_shape_representation);
    width: numeric_parameter;
    height: numeric_parameter;
END_ENTITY; -- Block_base_shape
```

The block_base_shape entity contains two parameters (width and height) representing the width and height of the base shape. In the manufacturing feature model, the thread feature can be represented in EXPRESS format as follows;

```
ENTITY thread
  ABSTRACT SUPERTYPE OF (ONE OF (defined_thread,
catalogue_thread))
  SUBTYPE OF (machining_feature);
    partial_profile: partial_area_definition;
    applied_shape: shape;
    inner_or_outer_thread: BOOLEAN;
    qualifier: OPTIONAL descriptive_parameter;
    fit_class: descriptive_parameter;
    form: descriptive_parameter;
    major_diameter: numeric_parameter;
    number_of_threads: numeric_parameter;
    thread_hand: descriptive_parameter;
END_ENTITY; -- Thread
```

The thread entity contains seven defined parameters and references to other two entities (partial_area_definition and shape). The partial_area_definition entity is

defined in EXPRESS as shown. Similarly; the `partial_area_definition` entity is defined by two defined parameters and one reference to another entity (orientation).

```
ENTITY partial_area_definition;  
    effective_length: numeric_parameter;  
    placement: orientation;  
    maximum_length: numeric_parameter;  
END_ENTITY; -- Partial_area_definition
```

3.5 Product Data Exchange in STEP

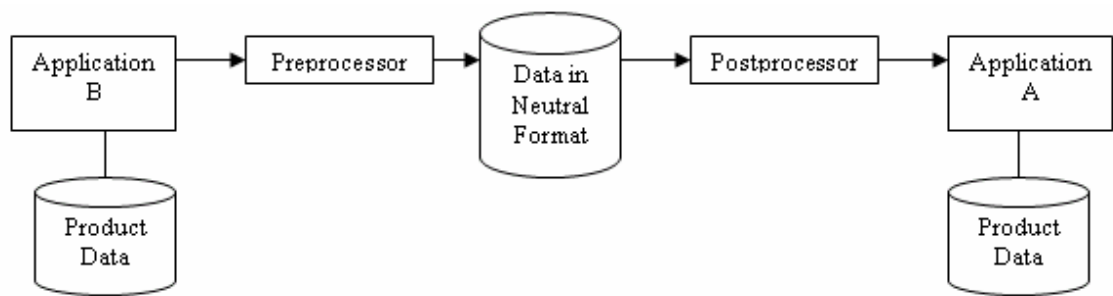
In a modern computing environment, data exchange is commonly understood to be the exchange of neutral format data files between computer systems. A sending system translates data from its internal format and encodes it into an established neutral format. This file is then transferred to the receiving system where the data is translated into the internal format of the receiving system (Carver and Bloom, 1991).

The architectural components that comprise a data exchange implementation include:

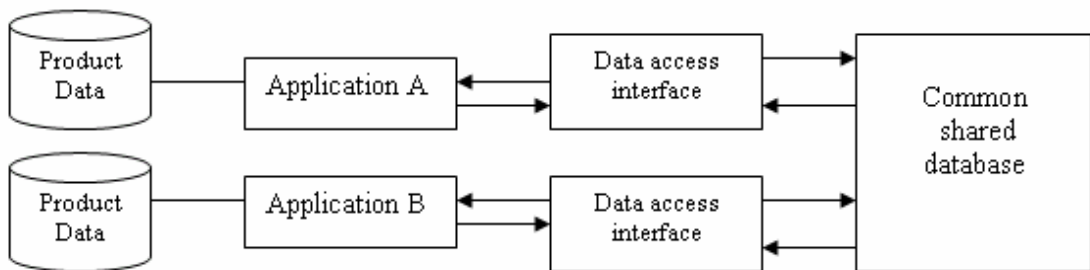
- a sending system translator (pre-processor) to generate neutral data file
- a transport mechanism for sending neutral files to the receiving system
- a receiving system translator (post-processor) to convert neutral data files to an internal format

There are two distinct approaches to data exchange: data translation and data sharing as shown in Figure 3.2. Data translation means that local input/output data of an application is interpreted into a neutral format via a preprocessor and is transformed for reuse by another application by its postprocessor. This is a straightforward approach because the data exchange is always between two systems at a time and each input/output file is translated independently. Data sharing means that all applications can access the same neutral data via some kind of data access interface and derive local data based on it (Carver and Bloom, 1991; Liang and Shah, 1999).

STEP supports data exchange through the ISO 10303 physical file format. Each ISO 10303 application protocol provides a model which serves as an explicit standardized data specification for an established application context. It is this model that provides a documented explanation of the context (scope) and meaning (relationships) of the data to be exchanged. It is used, along with an encoding algorithm, to produce ISO 10303 physical files that contain both the data and its associated context, thus enabling effective and flexible communication between computing systems (Liang and Shah, 1999).



a) Data translation



b) Data sharing

Figure 3.2 Product data exchange mechanisms

3.6 STEP Application Protocols

3.6.1 STEP AP 224

The official name is ISO 10303-224 "Application Protocol: Mechanical Product Definition for Process Planning Using Machining Features". STEP AP224 specifies the requirements for the representation and exchange of information needed to define product data necessary for manufacturing single piece mechanical parts. The product data is based on existing part designs that have their shapes represented by form features. AP224 covers the following (Sharma and Gao, 200):

- Product data that defines a single piece machined part to be manufactured.
- Product data that covers parts manufactured by milling or turning.
- Product data that is necessary to track down the customer order in the shop floor.
- Product data necessary to identify the status of a part in the manufacturing process.
- Product data necessary to track raw stock certification.
- For features that are necessary for defining shapes necessary for manufacturing.

The detailed descriptions and the implementation methods of this part of STEP will be described in chapter 4.

3.6.1 STEP-NC

STEP-NC is divided into two standards, ISO 14649 and ISO 10303 AP 238 (see Figure 3.3). ISO 14649 is the responsibility of ISO Technical Committee 184, Subcommittee 1 (TC I84 SC1). It defines the data requirements for machining. The first ISO 14649 publications are, ISO 14649-1:2003 Overview and fundamental

principles; ISO 14649-10:2003 General process data and ISO 14649-11:2003 Process data for milling. ISO 14649-1:2003 provides an introduction and overview of a data model for Computerized Numerical Controllers and explains its advantages and basic principle, based on the concepts of Product Data. ISO 14649-10:2003 specifies the process data which is generally needed for NC-programming within all machining technologies. These data elements describe the interface between a computerized numerical controller and the programming system (i.e. CAM system or shop floor programming system). On the programming system, the program for the numerical controller is created. This program includes geometric and technological information. It can be described using this part of ISO 14649 together with the technology-specific parts (ISO 14649-11, etc.). ISO 14649-10:2003 provides the control structures for the sequence of program execution, mainly the sequence of working steps and associated machine functions. The “machining schema” defined in ISO 14649-10:2003 contains the definition of data types which are generally relevant for different technologies (e.g. milling, turning, grinding). It includes the definition of the workpiece, a feature catalogue containing features which might be referenced by several technologies, the general executables and the basis for an operation definition. Not included in this schema are geometric items and representations, which are referenced from ISO 10303’s generic resources, and the technology-specific definitions, which are defined in separate parts of ISO 14649. ISO 14649-10 (2003) cannot stand alone. An implementation needs in addition at least one technology-specific part (e.g. ISO 14649-11 for milling, ISO 14649-12 for turning).

ISO 14649-11 (2003) specifies the technology-specific data elements needed as process data for milling. Together with the general process data described in ISO 14649-10, it describes the interface between a computerized numerical controller and the programming system for milling. It can be used for milling operations on all types of machines, milling machines and machining centers. Subject of the milling schema, which is described in ISO 14649-11:2003, is the definition of technology-specific data types representing the machining process for milling and drilling. This includes both milling of freeform surfaces as well as milling of prismatic workpieces (Suh et al, 2003).

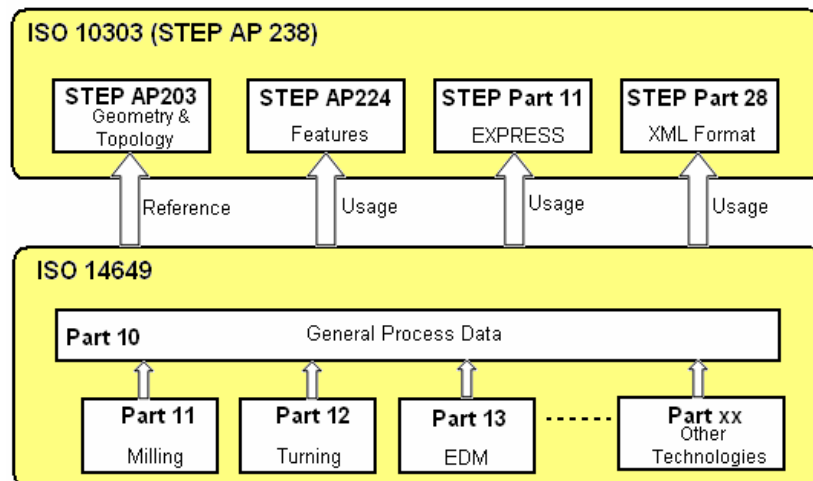


Figure 3.3 Base structure and context of STEP-NC data model

ISO 10303 AP 238 is the responsibility of ISO TC 184 SC4. It specifies the integrated resources necessary to describe the information requirements identified by ISO 14649 in a manner consistent with the part shape, feature, geometric dimension and tolerance information created by design and process planning activities and represented by APs 203 and 224. AP238 covers the following:

- Mechanical parts for manufacturing;
- Manufacturing process descriptions, including manufacturing operations, sequences of operations, and associated information as defined in ISO 14649;
- 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;

The detailed descriptions and the implementation methods STEP-NC will be described in chapter 5.

3.7 STEP Implementation

A STEP implementation is an application that uses this standard to exchange product information, or makes it possible for other applications to do so. Thus, STEP implementations cover the range from CAD systems, PDM systems and so forth, to stand-alone translators, to packages that make it possible to develop the above systems (Jekemmerer, 1999).

STEP implementations fall into several categories. Translators take data from pre-existing systems and convert it into STEP AP defined data. The tool converts non-STEP data into STEP data. Other applications might take STEP data as input, and then perform some function on it, generating more STEP output. An example of such a thing would be an application that takes partial AP information from several sources, like geometry from a CAD system and configuration information from a CM system, and then merges them into a complete AP exchange file. Another category might be an application that takes specific AP data and performs some analysis on it, such as a finite element package or a geometry visualizer. These applications should all work from STEP exchange files and possibly a shared database as well, so it is important to consider how the application will be tied to the EXPRESS information models of the various APs that they will work with (Jekemmerer, 1999; Peny and Trappey, 1998).

In summary, the following are general guidelines for implementing STEP:

1. Identification of the application business process that could benefit from a STEP Implementation.
2. Evaluation of the flow of the product data across its entire life cycle.
3. Selection of the Application Protocol that matches the requirements.
4. The following details must be known to the Engineers responsible on the implementation process:
 - What that Application Protocol is designed to do.
 - How many options it provides.
 - How many of those are implemented by their CAD vendors
 - How to select these options in their CAD Systems.

CHAPTER 4

FRAMEWORK OF THE STEP-FM SYSTEM

4.1 Introduction

A huge research work has been carried out for more than two decades mainly to integrate design, CAD and manufacturing, CAM. It was recognized that in order to achieve CAD/CAM integration, it is necessary to devise part models that contain more information than geometry and topology. CAD systems have become a common tool in industries to design parts, but the level of part model data is too low. Part models in CAD system (2D or 3D) are represented at a low level, such as: geometry for wireframe models, geometry and topology for B-rep models and primitives and operators for CSG models (Allada and Anand 1996). None of them can be directly used in downstream applications, such as CAM activities. This is because information on higher-level features is missing such as tolerances, material specification, and technological data related to manufacturing (Li et al. 1991). In an effort to overcome this shortcoming, feature-based modeling has been introduced. One of its advantages over conventional geometric modeling is the ability to associate not only geometric and topological information, but also form features, tolerances, material properties and other information which may be used during the process planning.

This chapter presents a STEP-based feature modeler (STEP-FM) for mechanical parts. High-level 3D solid features are used as the basic entities for part design. In modeling a part, STEP-FM employs the approach of "destructive modeling with features". The modeler relies on three main steps; (1) selection of the part base shape and overall size, (2) selection of the features to be added to or

subtracted from the part being designed, and (3) providing information needed to define feature size, position, orientation and other attributes such as surface finish, tolerances, etc. The designed part is then exported as a STEP XML data format (according to ISO 10303-AP224). This file can be used to integrate into CAPP/CAM systems without using a complex feature recognition process. An object-oriented approach is used in the definition and implementation of the product model (Amaitik and Kilic, 2002). This approach offers advantages of incremental system development and reusability. An example is given to demonstrate the application of the developed modeler. The remainder of the chapter presents a detailed analysis of the development steps of the STEP-FM system.

4.2 Architecture of STEP-FM System

An approach of using STEP-based machining features has been implemented in a feature-based modeler system (STEP-FM). STEP-FM is developed as an object-oriented feature-based design system to support concurrent design, automated process planning, and mechanical assembly (Motavalli et al, 1997; Perng and Chang, 1997; Kim et al, 1996). Figure 4.1 shows the structure of STEP-FM system. It consists of the following processes:

- Part base shape selection.
- Feature construction and attachment.
- Feature attributes definition.
- Feature STEP data generation.

Generally, part design process in STEP-FM system starts with selection of the part base shape. The dimensions of the selected part shape are assigned to define the size of the initial material. In the feature construction and attachment processes, feature is instanced and constructed using the main dimensions and then placed on the selected face of the part. Boolean-operation process is used to carry out union,

subtraction and intersection with the part. Features attributes can be defined right after the attachment of the feature. Such attributes including tolerances attributes, textual attributes and other attributes. These processes are repeated until all features are attached to the part. After that, feature data based on STEP-XML format is generated and prepared to be export. A more detailed description of STEP-FM system development process will be described in the following sections.

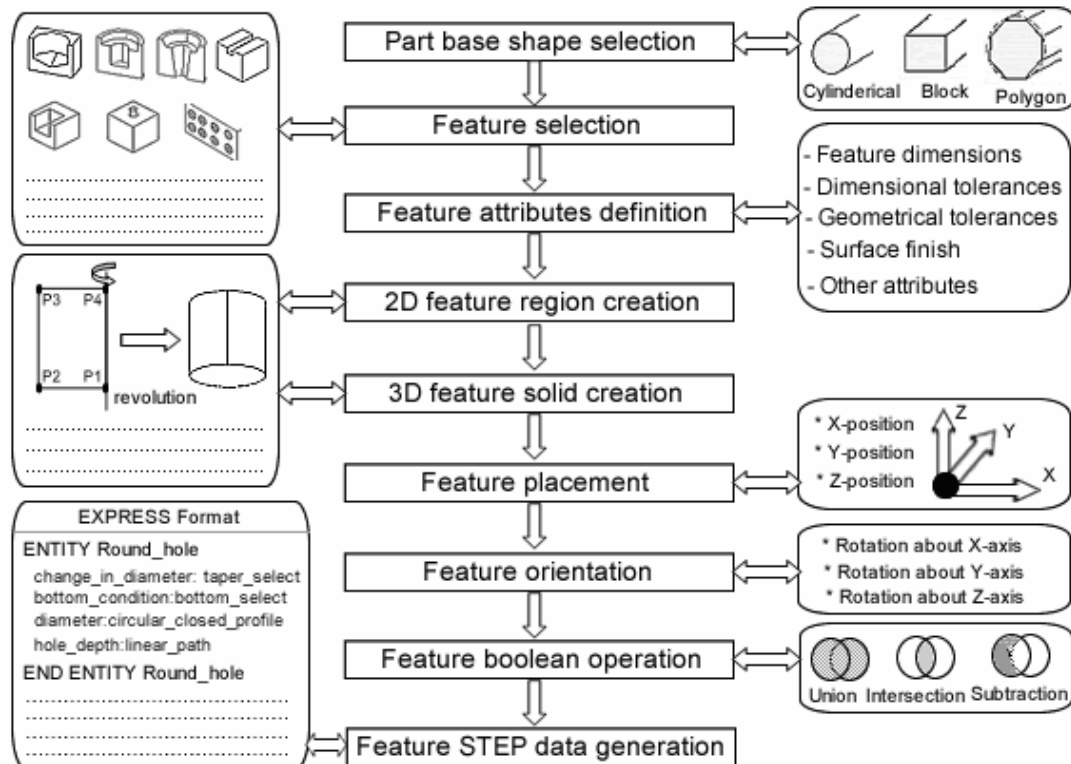
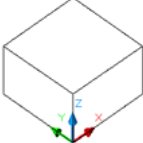
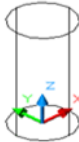
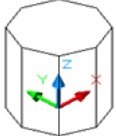
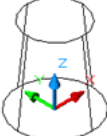

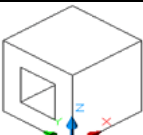
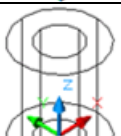
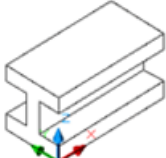
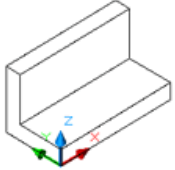
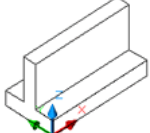


Figure 4.1 Architecture of STEP-FM

4.3 Part Base Shape

In STEP-FM system, the first step in designing a part is to specify the part base shape and the dimensions associated with the shape to define its size. The part base shape is then considered as the initial shape of the material before machining the features. Table 4.1 presents the different types of part base shapes supported by STEP-FM. Each base shape is defined by its name, shape size parameters, location, and orientation.

Table 4.1 Part base shapes

Part base shape	Base shape solid
Block base shape	
Cylindrical base shape	
Prismatic base shape	
Conical round base shape	
Conical prismatic base shape	
Rectangular tube base shape	
Round tube base shape	
I-base shape	
L-base shape	
T-base shape	

The block base shape describes the initial shape of the material as a rectangular cross section. Shape length, width and height are the parameters needed to define the size of the block shape. A Block base shape shall be positioned with the z-axis parallel to the height of the shape, the y-axis shall be parallel to the width of the shape, and the x-axis shall be parallel to the length of the shape. The axis shall be positioned in the left lower corner rectangular profile of the block base shape.

The cylindrical base shape is the initial shape of the material which is cylinder. Cylinder length and diameter are the main parameters needed to define the shape size. A cylindrical base shape shall be positioned with the z-axis parallel to the length of the shape. The x and y-axis shall be orthogonal to the z-axis. The axis shall be positioned in the exact center of the circular profile at the bottom of the cylindrical base shape.

The prismatic base shape describes the initial shape of the material as a polygon with a number of sides. Shape length, number of polygon sides, and circumscribed diameter are the parameters needed to define the prismatic shape. A prismatic base shape shall be positioned with the z-axis parallel to the length of the shape, the x-axis shall be parallel to at least one side of the prismatic shape, and y-axis should be orthogonal to the x and z-axis. The axis shall be positioned in the exact center of the polygon profile at the bottom of the prismatic base shape.

The conical round base shape and the round tube base shape are defined in a similar manner as the cylindrical base shape. The conical prismatic base shape is defined similar to the prismatic base shape. The rest of block-like shapes are defined according to their basic dimensions and positioned exactly same as block base shape.

4.4 Features Library of STEP-FM System

Features supported by STEP-FM are restricted to a set of 3-axis milling operation features, based on STEP AP224 developed for mechanical product definition for computerized process planning using form features. Figure 4.2 shows a

portion of the feature classes defined in STEP AP224. They are categorized into three types: machining, transition and replicate features. A *machining feature* is defined as a shape that represents volumes to be removed by machining to obtain the final part geometry from the initial stock. Machining feature requires both direction and location in placing it on a part. A *transition feature* is a transition area between two surfaces. This feature differs from machining feature in that it requires no orientation for placement. A *replicate feature* is a base shape, and the arrangement of identical copies of that base shape. Each base shape is a machining feature oriented to the first defined position of a pattern. The patterns (circular, rectangular and general) describe how to replicate that feature to different placements on the part. Table 4.2 presents the definition of these features according to the STEP AP224 definitions.

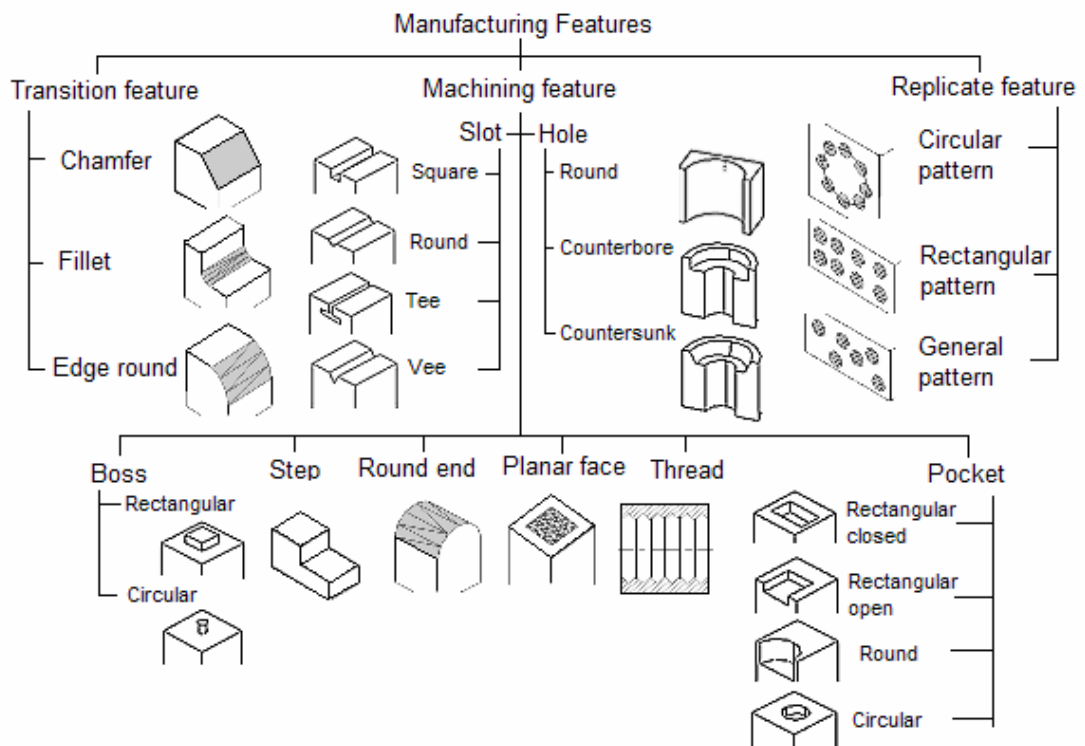


Figure 4.2 A part of feature classification in STEP AP224

Table 4.2 STEP-FM features definition

Feature	Definition
Hole	A Hole is a type of multi-axis feature that is the removal of a cylindrical volume from a part. Each Hole is either a counterbore hole, countersunk hole, or a round hole.
Pocket	A Pocket is a type of multi-axis feature that is a volume with a specific shape, removed from the part. The sides of a pocket may be parallel to the pocket's orientation vector coming out of the pocket or the sides may be tapered. Each pocket is either a general pocket, rectangular closed pocket, or a rectangular open pocket.
Slot	A Slot is a type of multi-axis feature that is a channel or depression with continuous direction of travel. Each slot is either a square slot, round slot, tee slot or a vee slot.
Boss	A Boss is a type of multi-axis feature that is a closed shape that protrudes from the surface of the part. The intersection of the boss and the base surface may have a radius shaped blend between them. Each Boss is either a circular boss or a rectangular boss.
Step	A Step is a type of multi-axis feature that is a linear sweep of a shape. The shape shall be specified by two lines that connect at a point and extend infinitely. The enclosed angle shall be smaller than 180 degrees. The intersection of the two lines need not be blended with a radius.
Thread	A Thread is a type of machining feature that is a ridge of uniform section on the form of a helix on the external or internal surface of a cylinder.
Planar face	A Planar face is a type of multi-axis feature that is an unbounded planar cut of a part. The Planar face shall have an orientation such that the Z-axis is the direction away from the part.
Marking	A Marking is a type of machining feature that is one or more text characters on a surface of a part.
Rounded End	A Rounded end is a type of multi-axis feature that is a partially circular shape passed along a linear path.

Table 4.2 (Continuous) STEP-FM features definition

Feature	Definition
Chamfer	A Chamfer is a type of transition feature that is a transition between corresponding edges of two joining non-coplanar surfaces, having a flat cross section.
Fillet	A Fillet is a type of transition feature that is a concave circular arc transition between two intersecting surfaces. The blend surface may be tangent to both of the adjacent surface edges.
Edge round	An Edge round is a type of transition feature that is a convex circular arc transition between two intersecting surfaces. The blend surface is tangent to both of the adjacent surface edges.

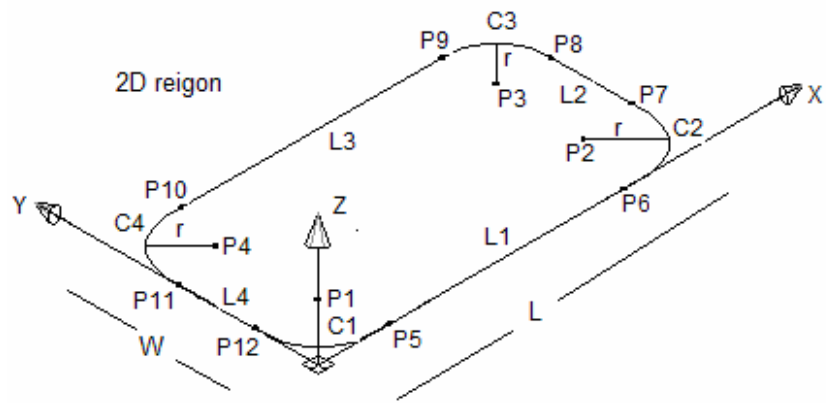
Appendix D shows the STEP-FM features library. These features are derived from the manufacturing features defined in STEP AP224.

4.5 Feature Creation

Feature creation in STEP-FM consists of two main stages. The first stage deals with the building of a two-dimensional feature region while the second stage deals with the generation of three-dimensional feature volume. The details of how these two stages are carried out will be explained in the following subsections.

4.5.1 Two-dimensional feature region creation

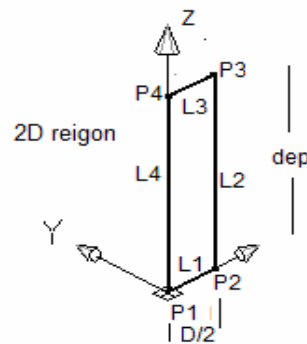
In this stage of feature creation, a two-dimensional feature region is created from the basic input dimensions of the feature. The created region is used to facilitate the generation of the 3D feature volume. Each feature in STEP-FM feature library has a 2D region definition in terms of its basic dimensions and insertion point. Appendix D presents the 2D region shapes and the associated parameters of STEP-FM features. For demonstration purpose, Figure 4.3 shows the creation process of 2D regions of rectangular closed pocket with round corners, while Figure 4.4 shows the creation process of round hole feature.



$P0(L/2, W/2, h)$	$P1(r, r, 0)$	$P2(L-r, r, 0)$
$P3(L-r, W-r, 0)$	$P4(r, W-r, 0)$	$P5(r, 0, 0)$
$P6(L-r, 0, 0)$	$P7(L, r, 0)$	$P8(L, W-r, 0)$
$P9(L-r, W, 0)$	$P10(r, W, 0)$	$P11(0, W-r, 0)$
$P12(0, r, 0)$	$L1(P5, P6)$	$L2(P7, P8)$
$L3(P9, P10)$	$L4(P11, P12)$	$C1(P1, r, 180^\circ, 270^\circ)$
$C2(P2, r, 270^\circ, 0^\circ)$	$C3(P3, r, 0^\circ, 90^\circ)$	$C4(P4, r, 90^\circ, 180^\circ)$

L = pocket length, W = pocket width, h = pocket depth
 r = corner radius, $P0$ = pocket insertion point.

Figure 4.3 rectangular closed pocket 2D region creation



$P1(0, 0, 0)$	$P2(D/2, 0, 0)$
$P3(D/2, 0, dep)$	$P4(0, 0, dep)$
$L1(P1, P2)$	$L2(P2, P3)$
$L3(P3, P4)$	$L4(P4, P1)$

D = Hole diameter
 dep = Hole depth
 $P1$ = Hole insertion point

Figure 4.4 round hole 2D region creation

4.5.2 Three-dimensional feature volume generation

The second stage of feature creation in STEP-FM is the three-dimensional feature volume generation. In this stage, a feature volume is generated by revolution or extrusion of the created 2D region about or along a specified axis. Appendix D presents the 3D features volumes and the method of generation of these volumes from 2D regions.

To demonstrate the 3D feature volume generation, Figure 4.5 shows the generation of 3D pocket feature volume by extruding the 2D region along the z-axis by amount equal to pocket depth. While, Figure 4.6 shows the generation of 3D round hole feature volume by rotating the 2D closed region about z-axis by an amount of 360 degrees.

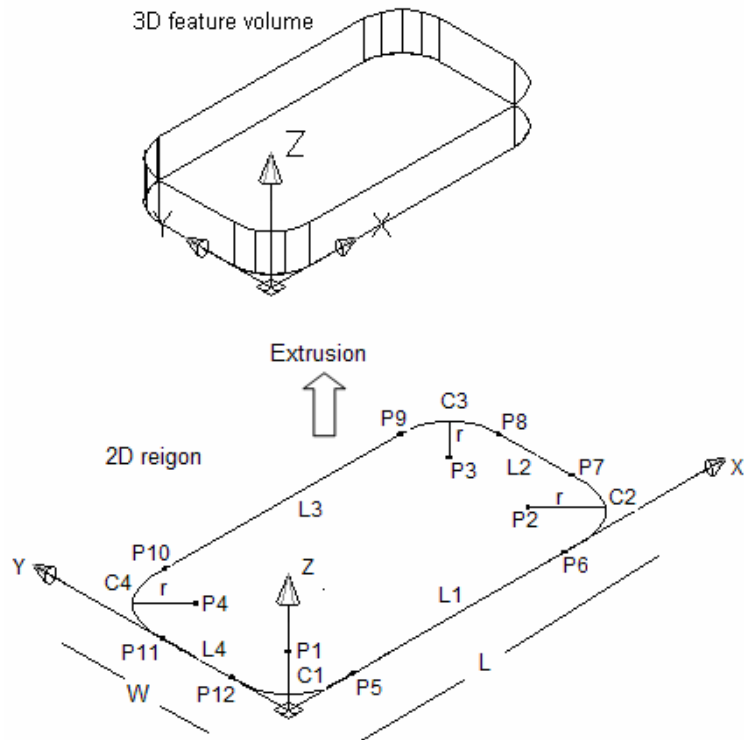


Figure 4.5 pocket feature construction process

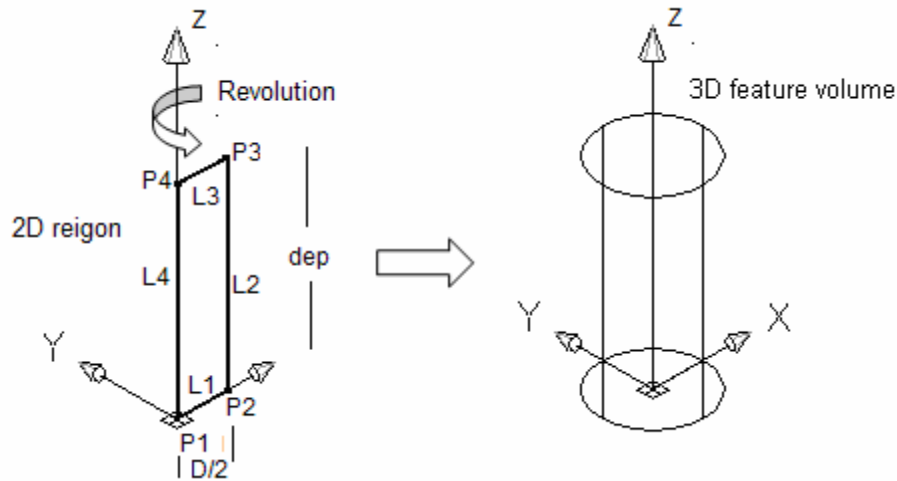


Figure 4.6 hole feature construction process

4.6 Features Attachment

Feature attachment is the process by which the user includes a new feature in the part under design (Chen and Hoffmann, 1995). Feature attachment in STEP-FM consists of a number of steps. First, the feature to be attached is selected visually by its name and then the user provides interactively the minimal and sufficient information needed to define the feature. Second, after generating the feature, the feature position is fixed by placing the feature in the specified insertion point in the part. Third, the feature orientation is adjusted by specifying the part face upon which is to be attached. Finally, feature Boolean operation is performed by subtracting, intersection or adding the feature to the part under design. The following subsections describe the feature attachment in more details.

4.6.1 Feature location

Two types of coordinate systems are used in STEP-FM to locate the part to be designed and its features. These two systems are defined as Part Coordinate System (PCS) and Feature Coordinate System (FCS). The PCS of rectangular prismatic part

is positioned in the left bottom corner of the part shape. The feature location is fixed by placing the feature in the specified insertion point in the part with respect to PCS. This insertion point will be considered as the FCS of that feature. The importance of introducing FCS comes in the process planning task. FCS can be used by process planners to specify the starting and ending points of machining the selected feature. Figure 4.7 illustrates the feature location and the coordinate systems.

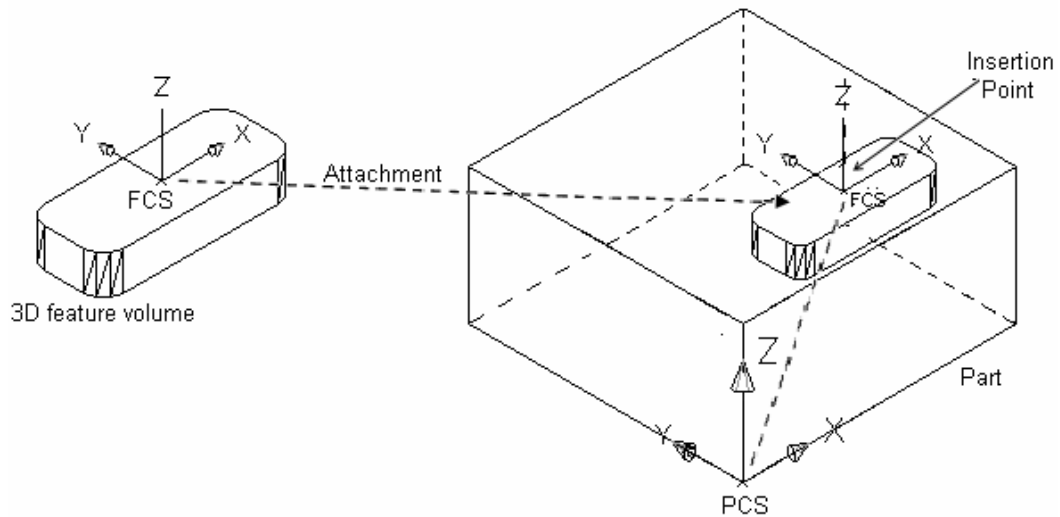


Figure 4.7 locating machining feature in the part

4.6.2 Feature orientation

Feature orientation in STEP-FM is carried out by two main steps. First, the feature is placed perpendicularly on one of the six face of the part. The faces are defined as shown in fig. 4.8. The second step is done by rotating the feature about a normal axis to the feature with a specified rotation angle (FIGURE 4.9). The direction cosines are used to specify the orientation of the FCS of the feature with respect to the PCS. The direction cosines of the feature orientation are the cosines of the angles between the FCS axes and each of the PCS axes as shown in Figure 4.10.

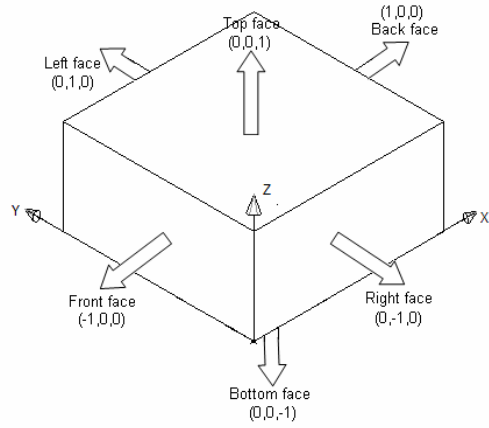


Figure 4.8 feature orientation

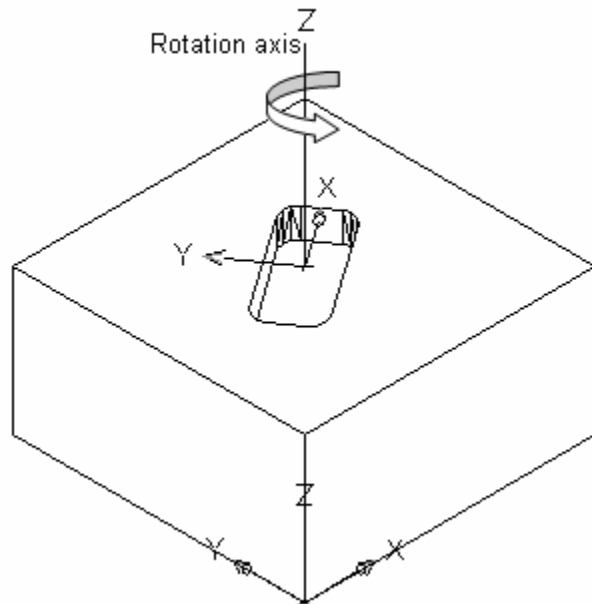


Figure 4.9 feature ROTATION

It is conventional to label direction cosines as l , m , and n and they are given by

$$l_x = \cos \alpha_x, m_x = \cos \beta_x, n_x = \cos \gamma_x$$

$$l_y = \cos \alpha_y, m_y = \cos \beta_y, n_y = \cos \gamma_y$$

$$l_z = \cos \alpha_z, m_z = \cos \beta_z, n_z = \cos \gamma_z$$

Where

$\alpha_x, \beta_x, \gamma_x$ are the orientation angles of the FCS x-axis with respect to the x, y, z of the PCS respectively.

$\alpha_y, \beta_y, \gamma_y$ are the orientation angles of the FCS y-axis with respect to the x, y, z of the PCS respectively.

$\alpha_z, \beta_z, \gamma_z$ are the orientation angles of the FCS z-axis with respect to the x, y, z of the PCS respectively.

Similarly;

l_x, m_x, n_x are the direction cosines of the FCS x-axis with respect to the x, y, z of the PCS respectively.

l_y, m_y, n_y are the direction cosines of the FCS y-axis with respect to the x, y, z of the PCS respectively.

l_z, m_z, n_z are the direction cosines of the FCS z-axis with respect to the x, y, z of the PCS respectively.

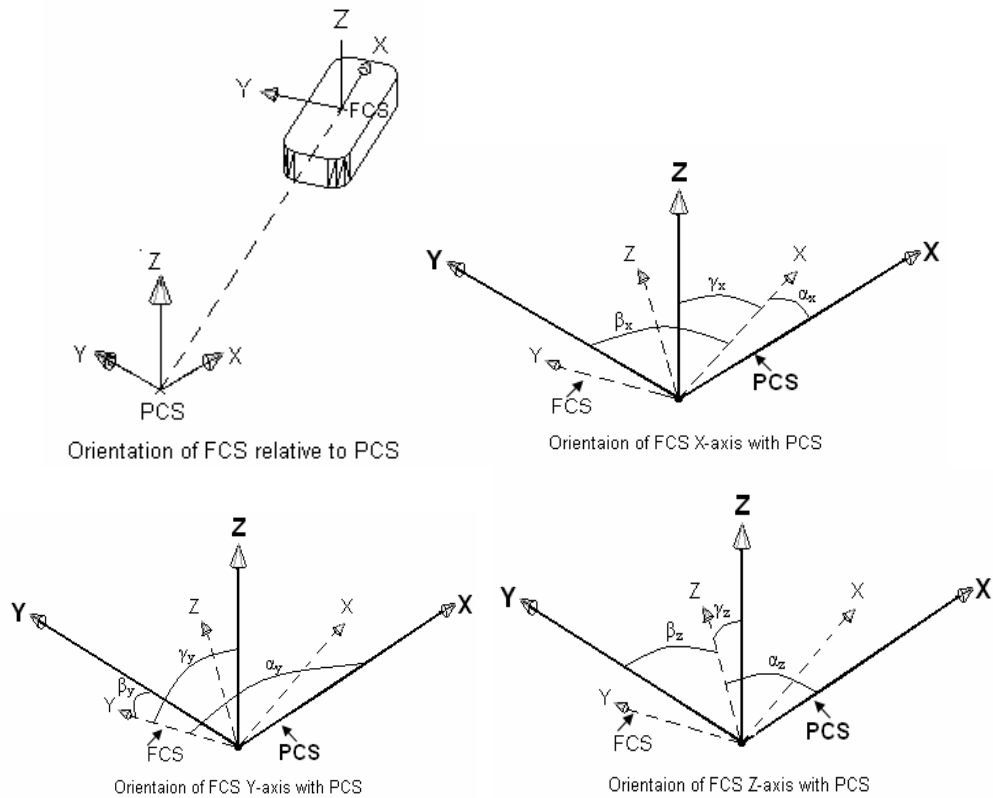


Figure 4.10 direction cosines of FCS

4.7 Technological Attributes Attachment

In general, CAD systems can only return geometric representations (i.e. wireframe, surface or solid representation). Important engineering specifications (tolerances, work material surface quality, etc.) are not always associated with the geometry and merely stored as text strings in CAD database. Nonetheless, this technological feature and workpiece information is as important as their geometry (Kruth, 1996). Especially for process planning applications, technological parameters like tolerances, surface finish, material hardness, etc. are as important (if not more) as the feature. Therefore, STEP-FM has been provided with the required interfaces and data structure required to attach technical attributes to workpiece and its attached features. These technical attributes can be grouped into four main categories namely; tolerances attributes, material attributes, textual attributes, and process attributes. The following subsections will provide a detailed explanation about the information associated with these attributes. Chapter 7 of this thesis will show the attachment mechanisms.

4.7.1 Tolerance attributes

Feature tolerances can be attached right after placing the feature on the part. STEP-FM provides a full suite of tolerances from STEP AP224 (see Figure 4.11) and generally classified into two types: dimensional and geometric tolerances. Each tolerance is a self-standing entity which may be applied to more than one feature, and several tolerances may apply to the same feature. The tolerance values are the values attached to the feature indicating the permissible amount of deviations. These values become attributes of that features and can be used while performing the process planning for the feature-based models generated by the system.

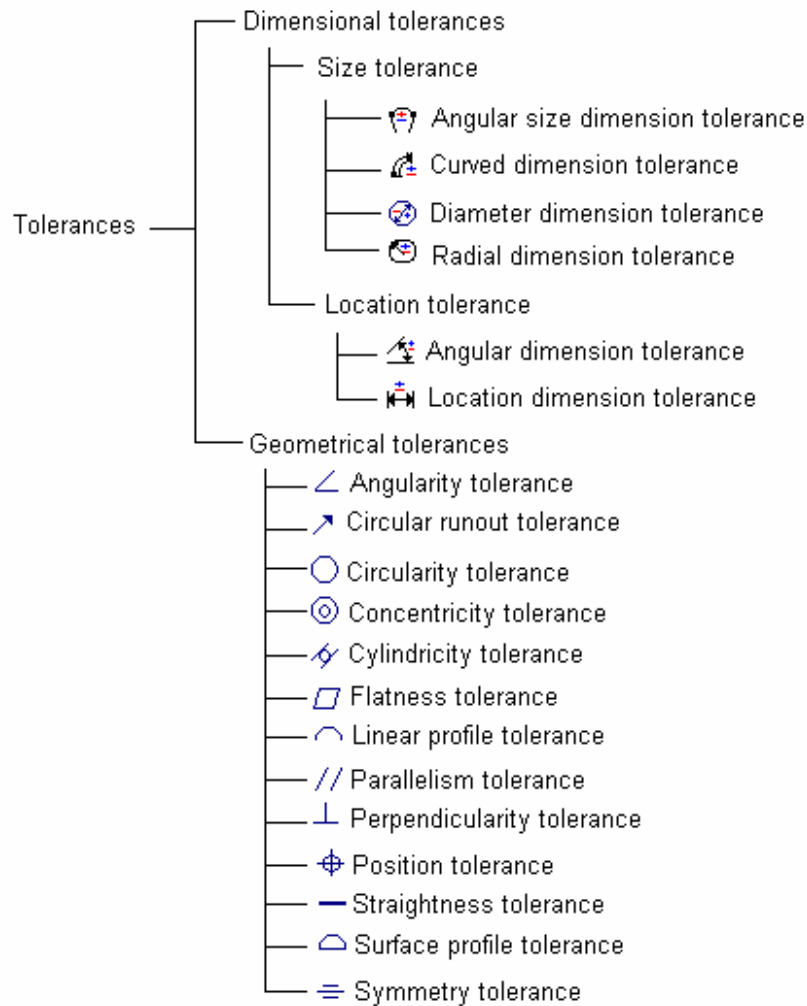


Figure 4.11 Dimensional and geometric tolerances from STEP AP224

Figure 4.11 shows the type of tolerances supported by STEP AP224 and implemented in STEP-FM. They are classified into two main groups namely; dimensional tolerances and geometrical tolerances. A dimensional tolerance indicates the total amount a specific feature dimension is permitted to vary, which is the difference between the maximum and minimum permitted limits of the feature dimension. A geometric tolerance indicates the maximum or minimum variation from true feature form or position that may be permitted in manufacture. Appendix F presents the definition of these tolerances and their application to the manufacturing features. Chapter 6 will demonstrate the attachment process of these tolerances and the parameters associated with each of them.

4.7.2 Material attributes

Material attributes are considered as part properties and used to identify the raw stock from which a part is to be produced. The part material identification includes primary and substitution material. According to STEP AP224, the parameters associated with material attributes can be summarized as follows:

- The material id specifies a word or group of words that make up the unique designation of the material.
- The material description specifies a user defined explanation of the material required for the part.
- The stock size specifies the dimensions of the raw material required to make the part.
- The material hardness specifies additional information to define hardness properties.

4.7.3 Surface attributes

In STEP-FM, surface attributes specify the characteristics of a surface that are elements of the shape of a feature or a part. Two important attributes are considered in the attachment of surface attributes. The first attribute is a surface finish and the second is a surface property. The latter can be defined by surface property name, value, and unit of measure used.

4.7.4 Process attributes

STEP-FM provides a process property which can be attached as series of actions or operations directed toward changing the feature or part properties. This

property can be defined by process name, process parameter, and the unit of measure used. Example of process property may be painting, coating, or heat treatment.

4.8 Features Data Generation

STEP-FM has a pre-processor designed to convert design data into a STEP XML data format. The pre-processor mechanism used in the translation process is based on two layers. In the first layer, usually known as logical layer, EXPRESS language is used to represent each feature in EXPRESS representation format which describes the parameters associated in the definition of the feature. The second layer of the pre-processor translator is known as physical layer. This layer defines the communication file structure called STEP file. This file transfer mechanism represents the static aspect of STEP which allows exchange of product data. This file is obtained by translating the EXPRESS entities defined in the logical layer to a STEP AP224 XML data format (Wyke et al, 2002; Pratt and Anderson, 2001).

An object-oriented approach has been implemented to facilitate the use of translation process from EXPRESS format to STEP XML format. All the EXPRESS entities defining STEP features have been programmed in class files. Each feature has an algorithm that uses the EXPRESS class files to generate the required STEP feature data format (Koonce and Judd, 2001; Rahimifard and Newman, 1996).

4.8.1 Output structure of STEP-FM system

STEP-FM output specifies an exchange structure format using XML representation (STEP Part 28) for product data of STEP AP 224 schema of which is specified in the EXPRESS language (STEP Part 11). The file format is suitable for the transfer of product data among computer systems. The mapping from the EXPRESS language to the XML representation is specified. Any EXPRESS schema can be mapped onto the XML exchange structure.

The exchange structure of XML representation consists of two types of elements; the header elements and the data elements. The header elements provide data relating to the exchange structure itself. The data elements provide the product data to be transferred. The exchange structure shall begin with a special root element "STEP-XML ISO 1030-28" followed by the header elements and the data elements. Immediately after the last data elements, the exchange structure shall be terminated by a special element "STEP-XML", see Figure 4.12.

The header elements shall appear exactly once in the exchange structure and shall be the first elements in the exchange structure. The structure of the header elements is specified in the next subsection. The data elements are collection of instances of the entities specified in the schemas identified in the header elements. The structure of the data elements is specified in the next subsection.

4.8.1.1 Header elements

Header elements contain information that is applicable to the entire exchange structure. These elements are presented in every exchange structure. Three header elements are specified and all required to occur exactly once in every exchange structure. The header elements are:

- The file description specifies the version of this part of ISO 1030 used to create the exchange structure as well as its contents.
- The file name provides human readable information about the exchange structure.
- The file schema indicates the EXPRESS schemas that specify the entity instances in data elements.

4.8.1.2 Data elements

Data elements contain the product data to be transferred by the exchange structure. The data elements are instances of entities that correspond to the EXPRESS schemas governing the exchange structure as specified in the header elements. The data elements shall begin with element "part" and shall be followed by the following elements (see Figure 4.12):

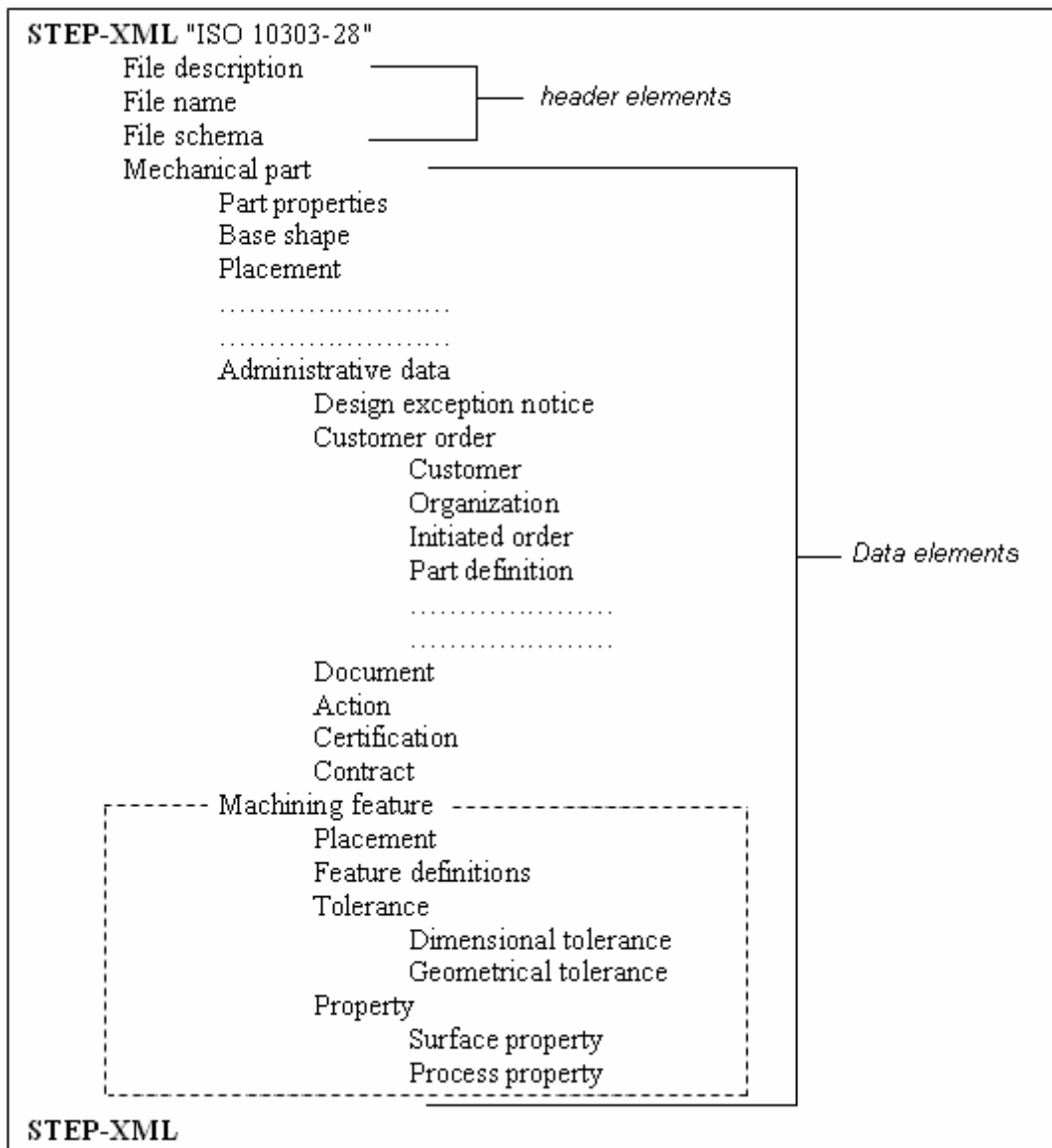


Figure 4.12 Part of output structure format of STEP-FM

- The part properties contain the description of characteristics of the part that is being defined. These characteristics specify requirements for manufacturing that apply to either the state of the part at a particular time prior to or after the manufacture of the part. Some of these properties include part material, alternative material, material hardness, surface property, etc.
- The base shape specifies the size and shape of the initial stock from which the part is to be produced. Placement element specifies the location and orientation of the part is also included.
- Administrative data contains information that identifies product data order information. These elements include work order information from an internal or external customer and internal manufacturing operations documentation that allows for the tracking of the work on a part's manufacture.
- The document element provides the ability to specify documents that are directly related to part data as they support the definition of the part. These documents may be specific to an operation on the part being manufactured or a property of a particular stage in the manufacturing process.
- The action element provides the description of actions, the reasons for these actions, and the states of these actions. These, for example, may include evolving user requirements, manufacturing problems, and difficulties that arise when a part is in use.
- The certification element assures and validates part data.
- The contract element describes the contract agreements.
- The machining feature element contains the information necessary to identify shapes which represent volumes of material that shall be removed from the part by machining or shall result from machining. This will be repeated in the structure according to the number of machining features exist in the part.
- The placement element specifies a set of axis and position to place the feature in the part.
- The feature definition element contains the information necessary to create a machining feature.
- The tolerance element contains the information necessary to identify the dimensional and geometrical tolerances of machining features.
- The property element contains the information necessary to define the surface and process properties of machining feature.

CHAPTER 5

FRAMEWORK OF THE ST-FeatCAPP SYSTEM

5.1 Introduction

Process planning has become a promising candidate for enhancing the adaptability and flexibility of manufacturing systems. It deals with the selection of manufacturing processes and parameters to transform a part from its initial form to final shape according to design specifications (Zhang & Alting, 1994). It is a function which systematically determines how a product is to be manufactured, so that the end product will be functional, economical, and of acceptable quality. There is much literature in the area of Computer Aided Process Planning (CAPP). Many new generations CAPP systems have been developed recently. These systems have the advantages of implementing advanced artificial intelligence techniques and integrated product data models. In terms of the application of artificial intelligence techniques in the development of CAPP, expert system and knowledge base approaches have been used to build CAPP systems since 1980s. However, the results are not so promising due to the knowledge acquisition bottleneck (Zhang and Huang, 1995). New advanced artificial intelligent techniques such as neural networks and fuzzy logic provide a promising approaches for automated knowledge acquisition and can be advantageously used in the building of new generation CAPP systems. This is due to their ability to acquire new knowledge and to cope with the dynamic changes of manufacturing systems. The literature documents several research efforts in the field of application of neural networks and fuzzy logic in CAPP systems (subsections 2.3.3 and 2.3.6).

In terms of integrating CAPP systems, the feature-based approaches have been recognized as essential tools for eventually integrating process planning and design. Section 2.2 presented a comprehensive review of these approaches. A survey on the application of feature-based approaches in CAPP systems was presented in subsection 2.2.9.

As revealed in the literature presented in this thesis, the application of neural networks and fuzzy logic are limited to discrete functions of CAPP systems, but has shown that these approaches can significantly improve the performance of CAPP systems. On the integration side, most of the feature-based models used in process planning have no standard explicit representation and the features are represented in an implicit data format.

This chapter focuses on developing a feature-based intelligent CAPP system called ST-FeatCAPP. The main purposes of this CAPP system are (1) to integrate a standardized feature-based model with process planning utilizing the concept of STEP-based features, (2) to develop a hybrid intelligent CAPP system by combining artificial neural networks, fuzzy logic, and rule-based techniques. The inference functions which will be used by the proposed CAPP system are classified into: (a) a neural network based function which means that certain CAPP sub-functions will be performed by utilizing the neural networks based inference method, (b) the fuzzy logic inference function which will be performed by adopting the fuzzy logic inference method, and (c) The rule-based function which describes that certain CAPP sub-functions will be carried out based on set of pre-defined rules, (3) to generate a digital process plan containing all the data required to produce the given part.

5.2 Architecture of ST-FeatCAPP System

Figure 5.1 shows the architecture of the proposed CAD/CAPP system. The overall system consists of two main subsystems: STEP-based feature modeler (STEP-FM) and STEP-based intelligent process planning (ST-FeatCAPP). The first

system was presented in the previous chapter. The second system which is the subject of this chapter consists of seven major components:

- Integration and preparation of part design data.
- Selection of machining operations.
- Selection of cutting tools.
- Selection of machine tools.
- Determination of machining parameters.
- Generation of setup plans
- Calculations of power and time.
- Generation of digital process plan.

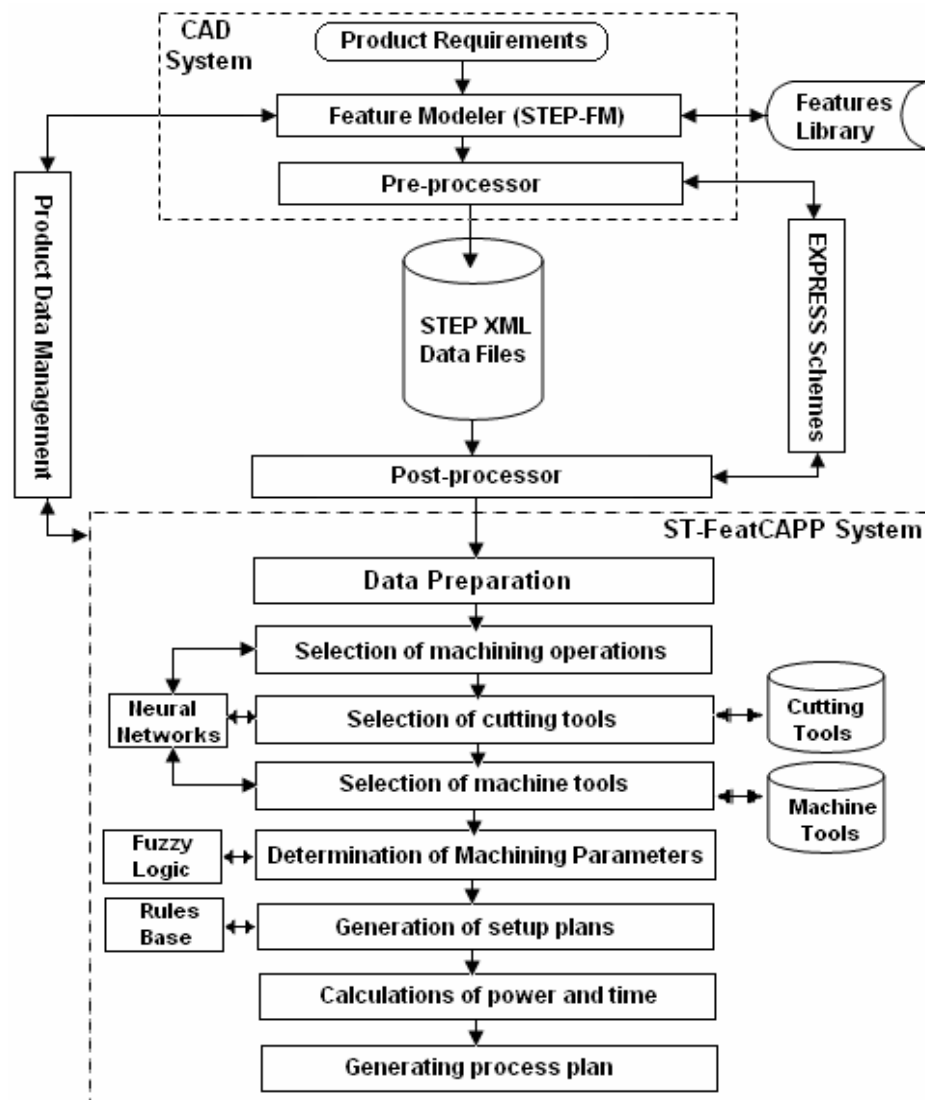


Figure 5.1 ST-FeatCAPP architecture

In the architecture, the part is first created by the feature modeler (STEP-FM) using a feature-based representation. The part design data is then generated by a pre-processor and saved in STEP XML file. This file will be passed to ST-FeatCAPP through two steps. The first step utilizes a post-processor to map step feature data and its associated attributes, while the second step prepare the mapped data to be fed to various ST-FeatCAPP tasks. Once the part data is entered to the system, the ST-FeatCAPP components can be carried out concurrently. In other words, the process planner can perform any task of ST-FeatCAPP at any time of the process planning cycle. The details on how ST-FeatCAPP components are implemented will be described in the following sections.

5.3 Integration of ST-FeatCAPP with CAD

One of the major concerns in integration of design and manufacturing is the automatic interpretation of design information for process planning. A huge research work has been carried out for more than two decades to solve this problem. The existing CAD systems can only provide geometrical modeling data rather than feature modeling data of designed parts. In order to automate the generation of process plans, a process planning system should be able to identify manufacturing features from the CAD database (Kank, 2003). For true integration of CAD with CAPP, a standard feature-based model is the efficient way to achieve this goal. Such model should contain explicit high-level part data in terms of feature attributes, tolerances, material specifications, etc. The model data can be used directly with process planning systems without using a complex feature recognition process (Devireddy and Ghosh, 1999; Patil and Pande, 2002; Wong and Wong, 1995). STEP is such a standard model to be implemented to solve this problem.

In this research work, the integration of ST-FeatCAPP system with CAD is implemented through STEP AP224 XML data generated by STEP-FM. This data is used for obtaining the type of machining features and their attributes (tolerances,

surface finish, etc.), which are present in the part. ST-FeatCAPP has a post-processor designed to convert design data (STEP AP224) into a suitable format to be used as input for process planning tasks. The post-processor mechanism used in the translation process is based on two layers (Amaitik and Kilic, 2002). In the first layer, usually known as logical layer, EXPRESS language is used to represent each feature in EXPRESS representation format which describes the parameters associated in the definition of the feature. The second layer of the post-processor translator is known as physical layer. This layer maps the communication file structure called STEP file and converts STEP data into EXPRESS schemes defined in the logical layer. These EXPRESS schemes can be interpreted easily and its contents can be passed to process planning tasks. Figure 5.2 shows a sample STEP AP224 and the mapping process.

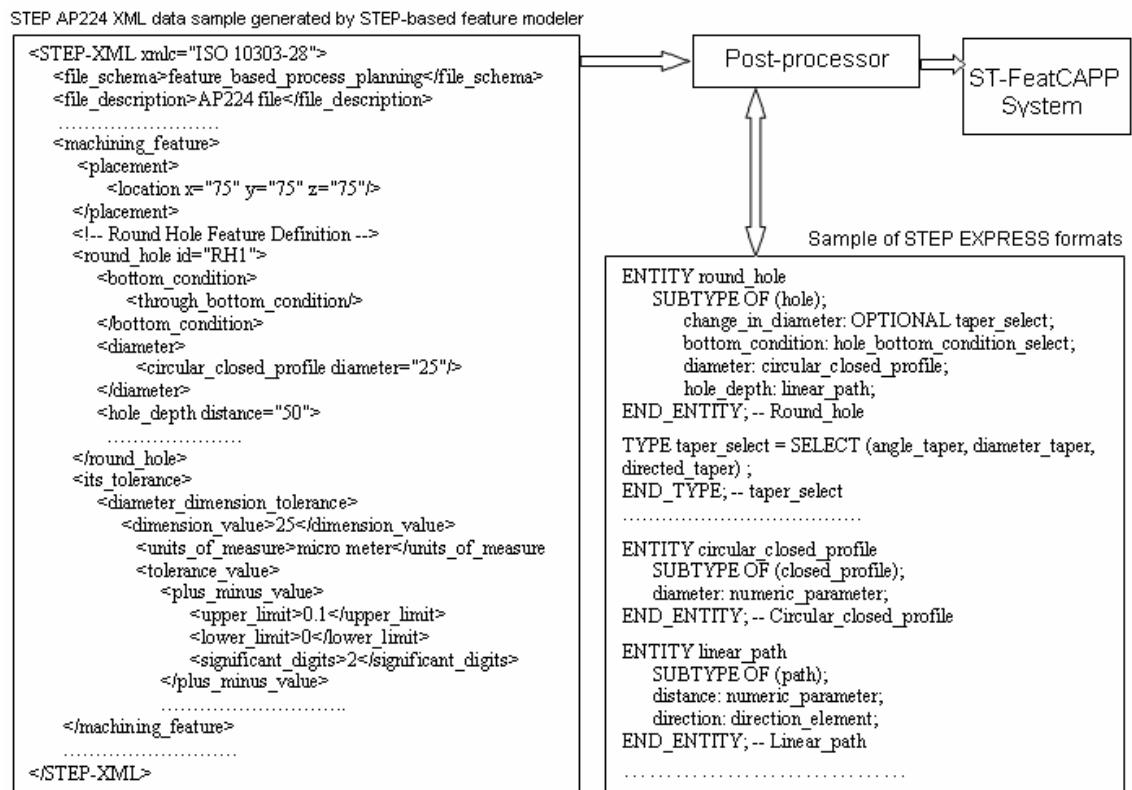


Figure 5.2 Mapping STEP AP224 data to ST-FeatCAPP system

5.4 Application of Artificial Neural Networks in ST-FeatCAPP System

Although the advantage of the application of artificial neural networks (ANNs) is evident, it is clear that their applicability in automated process planning still has to be verified (Santochi and Dini, 1996; Amper and Schmid, 1998; Monostori, et al, 2000). ST-FeatCAPP system uses three main neural networks to carry out some tasks of the process planning. These tasks are summarized as follows: selection of machining operations, selection of cutting tool, and selection of machine tools.

5.4.1 Selection of machining operations

In machining, the selection of operations is accomplished by two sets of operations namely; roughing operations and finishing operations. The roughing is to remove all material from the original raw piece surface down to the bottom or side of the feature minus the finishing allowance in multiple passes. The finishing will then remove the finish allowance to yield the final surface of the feature. For machining feature parameters, certain machining operations from each set will be selected. Moreover, this selection is made more difficult by the number of parameters defining the feature and the design requirements. Artificial neural networks can be used effectively to select the required machining operations for each feature (Ahmad and Haque, 2002; Zhang and Huang, 1995; Devireddy and Ghosh, 1999).

Machining operations involved in ST-FeatCAPP system are compliant with STEP-NC (ISO 14649). They define the machining process for a limited area of the workpiece. For the feature to they refer they specify, at a minimum, the tool to be used, and a set of technological parameters. ISO 14649 classifies machining operations into two groups: turning operations and milling operations. The machining operations considered in this research work are restricted to milling operations. Figure 5.3 shows a part of ISO 14649 machining operations classification involved in ST-FEATCAPP. Milling operations are grouped into two types: milling type operations and drilling type operations. Milling type operations are concerned with plane, side and bottom milling of machining features. Drilling

type are concerned with drilling a hole, reaming, sinking, etc. Cutting of thread is also included in drilling type.

This task functionally receives data for each feature in the part and generates the needed machining operations to realize the feature on the part. Figure 5.4 shows the neural network used to carry out the task of selection of machining operations in ST-FeatCAPP system. It consists of four fully connected layers, namely, the input layer, the output layer and the hidden layers. The input layer of the neural network consists of six input variables. The hidden layers have 15 neurons each that are decided by conducting a number of experiments. The output layer of the neural network consists of thirteen variables corresponding to the machining operations required for each feature on the part. Each output neuron has a value of 1 or 0. If the output neuron value is equal to 1 then it is interpreted as meaning that the selection of the machining operation is supported.

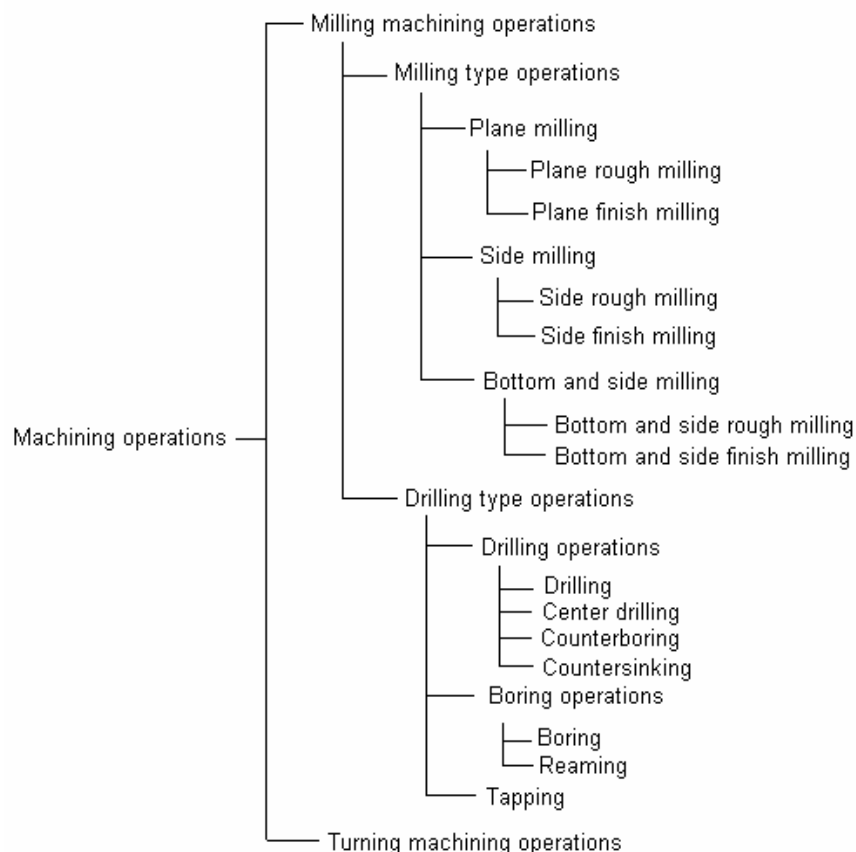


Figure 5.3 A part of ISO 14649 machining operations classification

The input values to the network corresponding to the feature type, feature condition, and feature thread are properly encoded to be interpreted by the neural network. The other input variables corresponding to feature dimension ratio, feature tolerance, and feature surface finish are scaled appropriately to be in the range between 0 and 1 to facilitate the training of the network.

The basic idea in this task is that for every machining feature there is a corresponding machining operation, depending upon the technological requirements of the feature. For example, for the same slot feature dimensions, if the tolerance or surface finish requirements are considered then finishing operation might be needed in this case and only roughing operation might be sufficient if these requirements are omitted. The neural network has been trained according to this criterion.

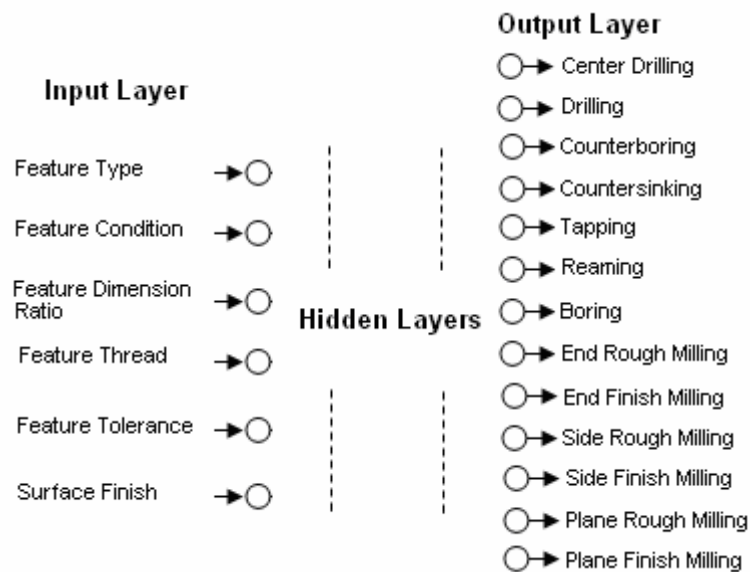


Figure 5.4 Machining operations selection neural network model

5.4.2 Selection of cutting tools

Tool selection is perhaps one of the most important functions in a process planning system because the selection of a cutting tool affects the selection of

machining parameters, production rate, cost of product, and the resulting accuracy (Usher and Fernandes, 1999). Within the field of traditional process planning, cutting tools are chosen by human intuition, but such a means of selection can be faulty, as it depends too much on the process planner's experience in determining the type and size of cutting tools and lacks a logical approach and consistent standard (Lin and Wei, 1997, Maropoulos, 2000). Therefore, in order to eliminate these problems; so as to be able to achieve machining automation, the development of computer-aided intelligent tool selection models are needed (Zhao et al, 2002).

The cutting tools library used in ST-FeatCAPP system is based on STEP-NC standard (ISO14649 Part 111). It consists of 20 cutting tools as presented in Appendix I. The tool selection process of ST-FeatCAPP is carried out in three overall steps. These steps will be described in the following paragraphs.

The first step utilizes a neural network model for selection a proper cutting tool for each machining feature. The selection is based upon machining feature and its associated machining operation. The basic idea in the selection process is that for each machining feature and machining operation combination there is a corresponding cutting tool to be used to generate that feature. For example, for square slot to be machined with an end milling operation, a flat end mill might be selected, while for round slot to be machined with the same machining operation, a ball end mill might be used. The neural network is trained based upon this criterion. Figure 5.5 shows the neural network model for cutting tool selection. It consists of five input variables, two hidden layers with fifteen neurons each and twenty output variables. The input variables correspond to feature type, feature attributes and machining operation type. The input values are appropriately encoded and scaled to facilitate the network training. The output variables are corresponding to the cutting tool types. Each output variable has a value of 1 or 0. If the output variable value is equal to 1 then it is interpreted as that the selection of the cutting tool is supported.

The second step of ST-FeatCAPP tool selection is then to search the cutting tools database to find standard tool dimensions that fit the machining setup (a number of Turkish standard documents related to cutting tools dimensions are used

in this step). The search criteria implemented depends on the application of the cutting tool in machining the selected feature. The following are some guidelines used for this purpose.

- Drilling type tool dimensions are selected based on the hole diameter to be drilled. The criterion is to find a cutting tool diameter equal to the hole diameter and the corresponding tool dimensions are then retrieved.
- Milling type cutter dimensions are selected based mainly on machined width and other secondary parameters. The criterion is to find a milling cutter diameter equal to or greater than the machined width and the corresponding tool dimensions are then retrieved.

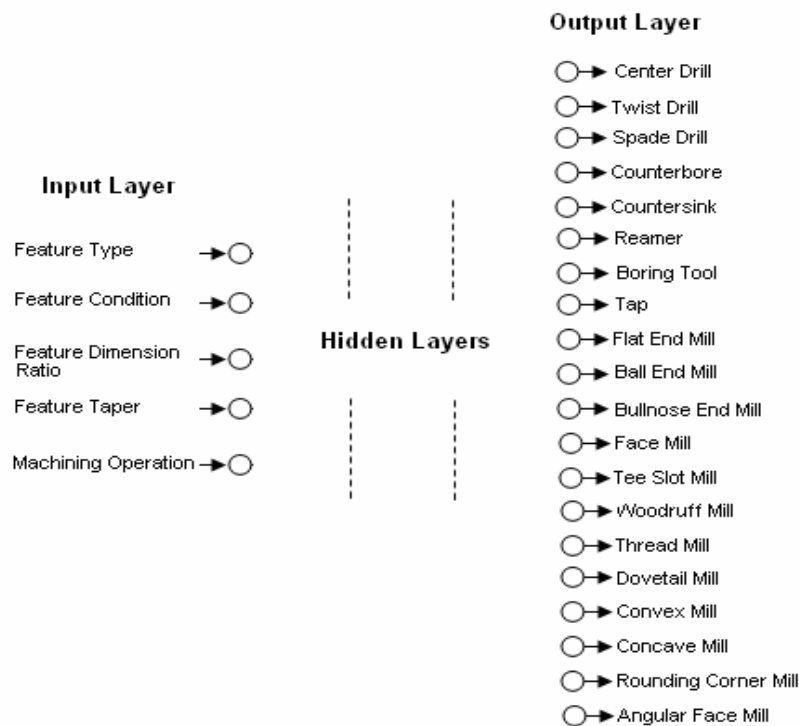


Figure 5.5 Cutting tools selection neural network model

The third step deals with selecting cutting tools geometry. For each cutting tool a neural network model was designed and trained to select the proper tool geometry. These proper tool geometry values are based on the recommendations collected from different machining handbooks and research outputs. These values can be treated as values obtained from a process planner expert on the shop floor. The users of ST-

FeatCAPP system do not have to stick to these values rather they can consider them as a guide to obtain the optimum cutting tool for a specific operation. The selection of these values is based on information about workpiece material and feature size. For demonstration purpose, Figure 5.6 shows the neural network model designed to provide the proper values of the twist drill geometry. The input parameters to the network are workpiece material type and hole diameter, while the output parameters are helix angle, point angle, land width, lip clearance, margin height and width, shank type, chisel edge, and web thickness. The input and output parameters of the cutting tools neural networks are summarized in Tables 5.1 to 5.6.

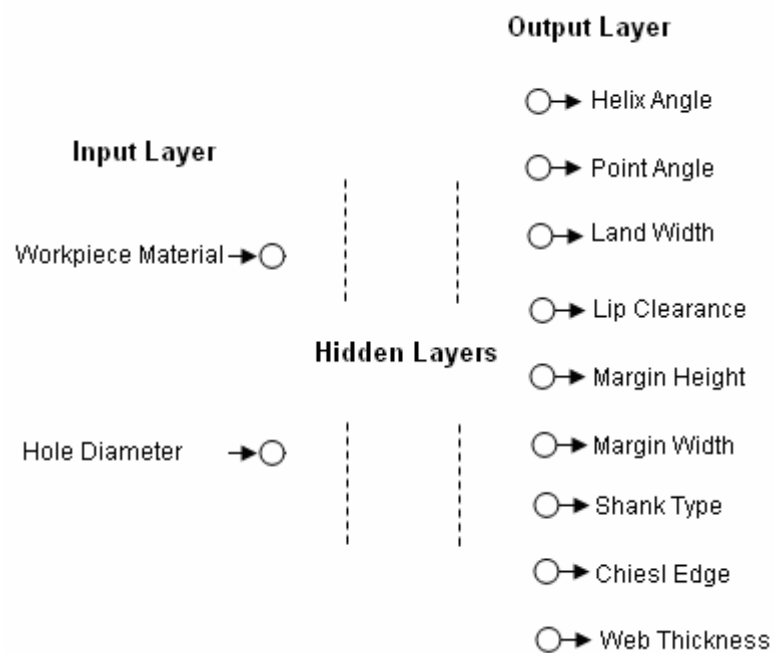


Figure 5.6 Twist drill neural network model

Table 5.1 Input and output parameters of twist drill neural networks

Input parameter	Output parameter
Workpiece material	Helix angle
	Point angle
	Land width
	Lip clearance
	Margin height
Hole diameter	Margin width
	Shank diameter
	Chisel edge
	Web thickness

Table 5.2 Input and output parameters of spade drill neural networks

Input parameter	Output parameter
Workpiece material	Web thickness
	Radius
Hole diameter	Point angle
	Circular land
Material hardness	Radius offset
	Primary relief angle
	Secondary relief angle

Table 5.3 Input and output parameters of reamer neural networks

Input parameter	Output parameter
Hole diameter	Primary relief angle
	Secondary relief angle
	Margin width
	Flute type
	Chamfer angle
Hole bottom condition	Primary chamfer relief
	Secondary chamfer relief
	Chamfer length
	Helix angle
	Number of flutes

Table 5.4 Input and output parameters of boring tool neural networks

Input parameter	Output parameter
Workpiece material	Back rake angle
	Side rake angle
	End relief angle
Workpiece hardness	Side relief angle
	End cutting edge angle
	Side cutting edge angle

Table 5.5 Input and output parameters of tap neural networks

Input parameter	Output parameter
Workpiece material	Point style
	Flute style
Thread major diameter	Rake (hook) angle
	Number of flutes
Workpiece hardness	Chamfer relief angle
Thread pitch	Spiral point angle

Table 5.6 Input and output parameters of milling cutters neural networks

Input parameter	Output parameter
Workpiece material	Helix rake angle
	Radial rake angle
Tool diameter	Radial relief angle
	Radial clearance angle
Material hardness	Cutting edge angle
	End relief angle

5.4.3 Selection of machine tools

This task of ST-FeatCAPP selects the machine tools on which the machining operations can be performed to produce the given part. This task is implemented using a neural network. The input vector of the neural network includes machining part characteristics (i.e. part type, part size, feature tolerances and feature surface finishes) and machining operation characteristics (i.e. operation type and machining power). The output vector of the neural network contains recommended specifications of the machine tool to be used to perform the task (Joo et al, 2001). These recommended specifications can be used as keys for search available machine tool database to find the proper machine tool. Figure 5.7 shows the neural network structure used for this task.

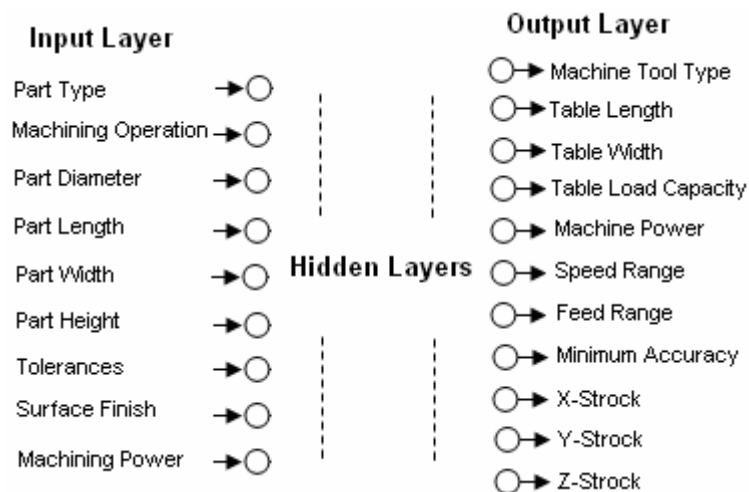


Figure 5.7 Machine tools selection neural network model

5.4.4 Training of neural networks

Once the neural network has been designed, it has to be trained to produce the expected output values in function of a predefined pattern of input values. This training operation is accomplished by selecting a proper training algorithm for the problem to be solved. Several training algorithms have been developed for ANNs. Many of these training algorithms are closely connected with a certain network topology. Among various existing training algorithms, Backpropagation algorithm was selected in this research work. It is commonly used algorithm, relatively easy to apply and has been proven to be successful in practical applications (Tsai et al., 1999; Tsoukalas and Uhrig, 1997; Fu, 1994). The main steps of this algorithm are described in the following subsection.

5.4.4.1 Encoding, decoding and normalizing input data

Data may have to be converted into another form to be meaningful to a neural network. How data are represented and/or translated also plays an important role in the network's ability to grasp the problem, that is, a neural network can learn more easily from some representations than from others. Data may be continuous-valued (e.g. $0 \rightarrow 1$) or binary (e.g. 0, 1). Sometimes data can be represented either as a single continuous value or as a set of ranges that are assigned binary representations. When the values are continuous, artificially breaking them up into groups can be a mistake, because it is often difficult for the network to learn examples that have values on or near the border between two groups. When there are naturally occurring groups, the binary categories are often the best method for making correlations. Based on the above mentioned review, the continuous-valued data inputs need to be scaled (normalized) and the binary type inputs needed to be encoded and decoded (Tsoukalas and Uhrig, 1997).

An encoding algorithm's function is to take data and convert it into a form suitable for presenting to the neural network. A decoding algorithm takes the values

of the output layer neurons and converts them into a meaningful answer. Encoding and decoding algorithms are neural-network-specific, but some guiding principles can be applied. Neurons operate with numeric inputs and outputs that correspond to the activation values of the neurons – that is, within the range neurons understand (usually $0 \rightarrow 1$ or $-1 \rightarrow 1$). The input encoding must interpret the raw data – that is, turn it into a sequence of numeric values that the network can understand. The output decoding must take a sequence of numbers that corresponds to the output neurons values and turn them into the form required for the final output (Tsoukalas and Uhrig, 1997; Vemuri, 1992).

Continuous-valued data must be normalized or scaled if it has a natural range that is different than the network's operating range ($0 \rightarrow 1$). Normalizing is simply dividing all values of a set by an arbitrary reference value, usually the maximum value. Use of the maximum value will limit the maximum value to unity.

To successfully apply neural networks in process planning many input variables have to be investigated and converted into a suitable format for presentation to the neural networks. In this research, the data representations of the neural network inputs are categorized into two groups. The first group has a continuous-valued data type and will be properly scaled; the second group has an enumerated data type and will be properly encoded and decoded. Tables 5.7 and 5.8 present the input variables used with the designed neural networks in ST-FeatCAPP system. Encoded, decoded and scaling factors are also presented to facilitate training and recalling processes of the neural networks

5.4.4.2 Backpropagation training algorithm

Backpropagation algorithm is a gradient decent method to minimize the total sum of square error over the entire training data set. The convergence to the optimal solution is accomplished by adjusting the weight connections through the partial derivative of the sum-squared error with respect to the weights. The following steps

summarize the implementation of this algorithm for training the designed neural networks (Tsoukalas and Uhrig, 1997; Fu, 1994, Vemuri, 1992).

Step 1

Set all the necessary network parameters such as the number of input neurons, the number of hidden layers and the number of neurons included in each hidden layer, the number of output neurons, etc.

Step 2

Set all network weights to small random values, positive and negative (-0.3 to 0.3).

Step 3

Initialize the iteration (epoch) number ($m=1$) and presentation (example) number ($n=1$).

Step 4

Apply one training sample to the input layer $[X_1, X_2, \dots, X_{N_k}]$ and note the corresponding desired output $[O_1, O_2, \dots, O_{N_k}]$, where N_k is the number of neurons in layer k .

Step 5

Calculate the output of the neurons layer by layer through the network, from the second layer to the output layer using:

$$O_j^{N_k}(n) = F\left(\sum_{i=1}^p W_{ji}(m)O_i^{N_{k-1}}(n)\right) \quad \text{for each neuron } j, 1 \leq j \leq N_k \text{ and } 2 \leq k \leq L$$

where L is the number of layers in the network.

F is a sigmoid activation function of the form $F(a) = 1/(1 + e^{-a})$.

$W_{ji}(m)$ is the weight connecting neuron i in layer k to neuron j in layer $k+1$.

$O_i^{N_k}$ is the output of neuron N in layer k .

Step 6

Calculate the error gradient δ for every neuron in every layer in backward order from output to the first hidden layer.

The error for the output layer neurons is computed by

$$\delta_j^{N_k}(n) = O_j^{N_k}(n)(1 - O_j^{N_k}(n))(T_j(n) - O_j^{N_k}(n))$$

for every neuron j , $1 \leq j \leq N_k$, $k=L$ where $T_j(n)$ is the target vector.

Then, successively, the error gradients for all hidden layer neuron are computed from;

$$\delta_j^{N_k}(n) = O_j^{N_k}(n)(1 - O_j^{N_k}(n)) \sum_{i=1}^{N_{k+1}} \delta_i^{N_{k+1}}(n) W_{ij}(n)$$

for every neuron j , $1 \leq j \leq N_k$, $k=L-1, \dots, 2$

At the end of the error backward propagation step, neurons of the network will have error values (except input layer neurons, $L=1$).

Step 7

Adjust the network weights for every layer. Starting at the output layer neurons and working back to the first hidden layer recursively adjust weights according to the generalized delta rule.

$$W_{ji}(m+1) = W_{ji}(m) + \eta \delta_j^{N_k}(n) O_j^{N_k}(n) + \alpha [W_{ji}(m) - W_{ji}(m-1)]$$

for every neuron j , $1 \leq j \leq N_k$, $k=L, L-1, \dots, 2$

where

α is momentum constant ($0 < \alpha < 1$) to smooth out the weight change and accelerate convergence of the network.

η is learning rate ($0 < \eta < 1$) controls the step size for weight adjustments.

Step 8

Repeat actions in steps 4 to 7 for every training sample.

Table 5.7 Neural network inputs coded values

Input variable	Code	Input variable	Code
Machining feature		Feature condition	
Round hole	0	Through hole bottom	0
Counterbore hole	0.5	Blind with flat hole bottom	0.1
Countersunk hole	0.1	Blind with spherical hole bottom	0.2
Square slot	0.15	Blind with conical hole bottom	0.3
Round slot	0.2	Blind with tapered hole bottom	0.4
Vee slot	0.25	Blind with radiused hole bottom	0.5
Tee slot	0.3	Planar pocket bottom	0
Circular boss	0.35	General pocket bottom	1
Rectangular boss	0.4	Open slot ends	0
Rectangular closed pocket	0.45	Open slot end and radiused end	0.1
Rectangular open pocket	0.5	Radiused slot ends	0.2
Round pocket	0.55	Open slot end and flat end	0.3
Circular pocket	0.6	Flat slot ends	0.4
Step	0.65	Woodruff slot ends	0.5
Rounded end	0.7	Open slot end and woodruff end	0.6
Planar face	0.75	Planar boss top	0
Chamfer	0.8	General boss top	1
Fillet	0.85	Machining operation	
Edge round	0.9	Center drilling	0.1
Workpiece material		Drilling	0.15
Free machining carbon steel	0.1	Counterboring	0.2
Carbon steel	0.2	Countersinking	0.25
Alloy steel	0.3	Tapping	0.3
Stainless steel	0.4	Reaming	0.35
Gray cast iron	0.5	Boring	0.4
Ductile cast iron	0.6	Bottom and side rough milling	0.45
Malleable cast iron	0.7	Bottom and side finish milling	0.5
Aluminum alloys	0.8	Side rough milling	0.55
Copper alloys	0.9	Side finish milling	0.6
Part base shape		Plane rough milling	0.65
Block base shape	0	Plane finish milling	0.7
Cylindrical base shape	0.1	Feature thread	
Prismatic base shape	0.2	No thread	0
Round conical base shape	0.3	Thread	1
Conical prismatic base shape	0.4	Feature taper	
Round tube base shape	0.5	No taper	0
Rectangular tube base shape	0.6	Taper	1
I-base shape	0.7	Tool materials	
T-base shape	0.8	High speed steel	0
U-base shape	0.9	Carbide	1
L-base shape	1		

Table 5.8 Neural network inputs scale factors

Input variable	Scale factor	Input variable	Scale factor
Feature dimension ratio	100	Table width	1000
Feature tolerance	1	Table load capacity	100
Feature surface finish	100	Machine power	10
Material hardness	1000	Maximum speed	1000
Tool diameter	100	Maximum feed	1000
Part diameter	100	Minimum accuracy	1
Part length	1000	X-stroke	1000
Part width	1000	Y-stroke	1000
Part height	1000	Z-stroke	1000
Machining power	10		
Table length	1000		

Step 9

Calculate the average sum-squared error resulted at the end of every training cycle. This error can be evaluated by the following expression.

$$sse = \frac{1}{2N} \sum_{j=1}^n \sum_{i=1}^{N_L} (T_{ij} - O_{ij}^L)^2$$

where T_{ij} is the target value desired for the i th output and for the j th example.

Step 10

Compare the average sum-squared error (sse) with the predetermined limit value (tolerance value) (ϵ) of the error, if it is less then stop. Otherwise, increase number of iterations and randomize the order in the training set and return to step 4.

5.4.4.3 Training data patterns

A successful neural network requires that the training data set and training procedure be appropriate to the problem. The training data set must span the total range of input patterns sufficiently well so that the trained network can generalize about the data. In order to have extrapolation and interpolation capabilities, neural networks must be trained on a wide enough set of input data to generalize from their training sets (Tsoukalas and Uhrig, 1997). To achieve this goal and demonstrate the applicability of the designed neural networks, a number of training patterns (each

pattern is formed by input and output vectors) are generated for each task. The input values of the training patterns are selected from within specified range for each input parameter. The output values are based upon the limitations put on each variable.

5.4.4.4 Training and testing experiments

Several training experiments have been carried out to identify the optimal network structure and best training parameters of the neural networks which produces minimum errors during training phase. The adopted procedure is schematically represented in Figure 5.8; after setting a meaningful set of examples to be initially used in training, a sample structure with a low number of neurons has been firstly considered; during the process, the complexity of the structure has been progressively increased until the network error reaches a value lower than a predefined limit. In this way, several training experiments (see Appendix G) with a different number of hidden neurons, learning rate, and momentum values have been checked.

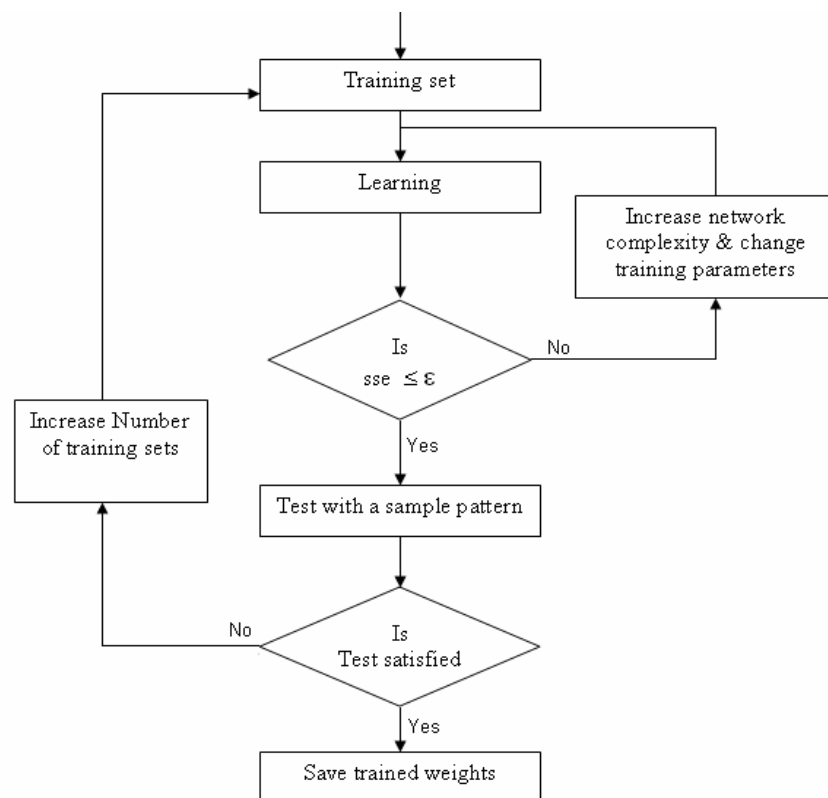


Figure 5.8 Training and testing procedure of neural networks

In particular, a given network structure has been considered able to correctly learn the training set if the following condition is satisfied:

$$sse \leq \varepsilon$$

where ε is the predefined limit value of the error (tolerance value) of the error and sse is the average sum square error resulted at the end of training process. During training the error limit (ε) has been set to 0.00001.

At the end of training phase, the generalization capability of the network is verified by a validation test presenting pairs of input and target vectors (test sample) describing intermediate situations with respect to those proposed in training. If the test sample produces an acceptable result then the neural network is validated; if the result is unacceptable, the following corrective actions are considered (Tsoukalas and Uhrig, 1997; Santochi and Dini, 1996):

- Reduction of the network complexity and changing the training parameters, supposing that this behavior is caused by overfitting phenomena.
- Increase of number of proposed training examples, adding to the training set the situations of the test sample which have generated unacceptable results.

In this research work, the second option has been adopted. It is obvious that modification of the training set requires to perform again the whole procedure of training and testing. At the end of this process, multi-layer feed-forward neural networks with a number of neurons for each layer listed in Table 5.9 have proved to be the best network structures.

The graphs shown in Figure 5.9 and 5.10 represent the training set average error on the y-axis against the number of epochs elapsed on the x-axis. Epochs represent a complete pass through the network of the entire set of training patterns. The graphs illustrate downward movement of the error rate as learning progressed, indicating that the average error decreased between actual and predicted results.

Table 5.9 Architectures and training parameters of the neural network models

Exp. No.	Network Name	Inputs	Outputs	Hidden Layers	Hidden neurons	η	α	Train pattern	epoch	sse
2	Hole	6	8	2	15	0.3	0.8	432	2179	0.00001
7	Slot	6	6	2	15	0.1	0.9	224	3000	0.000016
11	Pocket	6	6	2	15	0.3	0.8	168	429	0.00001
16	Boss	6	6	2	15	0.3	0.8	108	691	0.00001
21	Transition	6	6	2	15	0.3	0.8	144	569	0.00001
26	Step	6	6	2	15	0.3	0.8	96	883	0.00001
31	Planar face	6	6	2	15	0.3	0.8	96	826	0.00001
36	Rounded end	6	6	2	15	0.3	0.8	96	865	0.00001
43	Twist drill	2	9	2	12	0.4	0.6	135	3000	0.00018
46	Drilling tools	5	12	2	15	0.1	0.9	198	2000	0.00019
52	Milling tools	5	13	2	15	0.3	0.8	74	2000	0.000082
60	Spade drill	3	7	2	15	0.2	0.8	183	3000	0.00326
64	End mill	3	7	2	15	0.5	0.8	324	3000	0.00012
67	Reamer	2	10	2	15	0.3	0.8	122	3000	0.00072
73	Milling cutters	3	6	2	15	0.4	0.6	189	370	0.00001
76	Machine tools	9	10	2	15	0.3	0.9	13	5000	0.0001

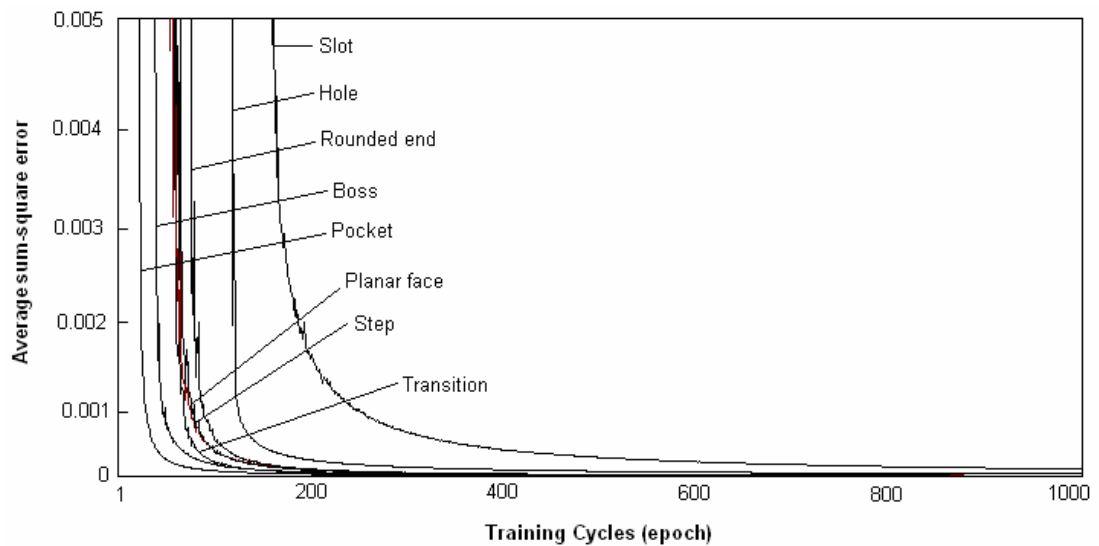


Figure 5.9 Training progresses of machining operations selection neural networks

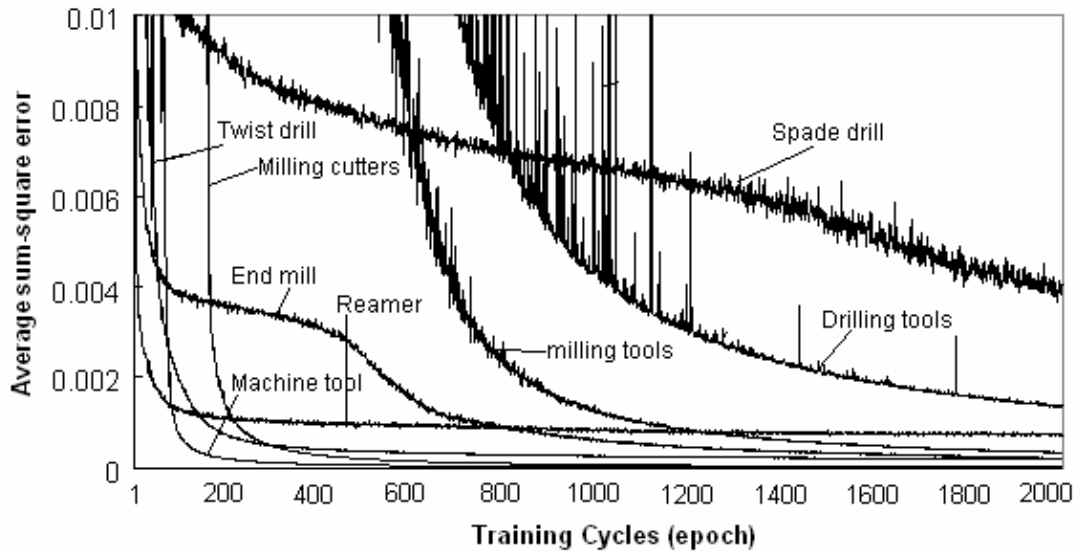


Figure 5.10 Training progresses of cutting tools and machine tool selection neural networks

5.5 Application of Fuzzy Logic in ST-FeatCAPP System

Machining parameters such as cutting speed and feed rate affect the production rate, quality and cost of a component during a machining operation. The selection of process parameters is traditionally carried out by process planners or experienced machinists, either on the basis of their experience on the shop floor or with the help of handbooks, for achieving the desired surface quality on the component. The parameters thus selected are generally on the conservative side to avoid machining failure (Prasad et al., 1997).

In the past decade, process planners have optimized the machining parameters using some optimization algorithms. The optimization of machining parameters is a nonlinear optimization with constraints, so it is difficult for traditional optimization algorithms to solve this problem because of the problems of convergence speed or accuracy (Liu and Wang, 1999).

Recently, process planners have started using artificial intelligent techniques, such as neural networks, fuzzy logic and genetic algorithms to select the machining

parameters and have made some progress (Chen and Kumara, 1998; EL Baradie, 1995, Liu and Wang, 1999; Wong and Hamouda, 2003). In this research work, several fuzzy logic models are developed to select machining parameters in drilling and milling type operations. In order to explain the steps involved in the development of these models, there are three basic components of fuzzy models which have to be described. These components are fuzzification of input and output variables, fuzzy rules applications, and defuzzification of the output variables [El Baradie, 1997]. The following subsections will explain detailed steps on how these components of the fuzzy model are implemented in ST-FeatCAPP system.

5.5.1 Fuzzification of input and output variables

Fuzzification is a mathematical procedure for converting an element in the universe of discourse into the membership value of a fuzzy set. Fuzzification dividing the input and output variables into fuzzy regions (sets). The first step of fuzzification process is to define the fuzzy sets in the input and output variables. The possible domain interval of both the inputs and outputs are divided into a number of regions in such away that they overlap each other. The length of region may differ for each variable and one membership function is assigned to each region (Ying, 2000; Tsoukalas and Uhrig, 1997).

The input variables in this research work are material hardness, hole diameter, depth of cut, and thread pitch. The output variables are cutting speed and feed rate. Table 5.10 presents the inputs, outputs, and the domain intervals of the variables used in the developed fuzzy models as well as the range of each variable. The universe of input and output variables have been partitioned according to their minimum and maximum values allowed to control the models. Table 5.11 shows the fuzzy sets of the variables and their associated values and labels. The number of fuzzy sets for each input and output variable is five sets. Each fuzzy set has a defined linguistic term and specified range which can be modified to control the fuzzy model.

Table 5.10 Domain intervals of input and output variables

Variable	Range	Unit
<i>Input variables</i>		
Material hardness	0 → 550	BHN
Hole diameter	0 → 80	mm
Depth of cut	0 → 10	mm
Thread pitch	0 → 4.5	mm
<i>Output variables</i>		
Cutting speed	0 → 250	m/min
Feed rate	0 → 1.5	mm/rev or mm/tooth

Although scientific publications have suggested many different types of membership functions of fuzzy logic, standard membership functions are used in most practical applications (Berkan and Sheldon, 1997; Nguyen and Walker, 1994). In this research work, a triangular membership function is used for all input and output variables. It is defined by the following equation:

$$Triangle(x, a, b, c) = \begin{cases} 0 & (x \leq a) \\ \frac{x-a}{b-a} & (a \leq x \leq b) \\ \frac{c-x}{c-b} & (b \leq x \leq c) \\ 0 & (c \leq x) \end{cases}$$

It has three parameters 'a' (minimum), 'b' (middle), and 'c' (maximum) that determine the shape of the triangle. Figure 5.11 shows a triangular membership function of a fuzzy set. Figure 5.12 shows the membership functions for the input and output variables of the developed fuzzy models

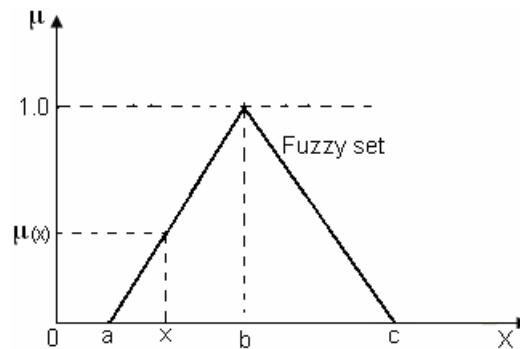


Figure 5.11 A triangular membership function of a fuzzy set

Table 5.11 Fuzzy sets of input and output variables

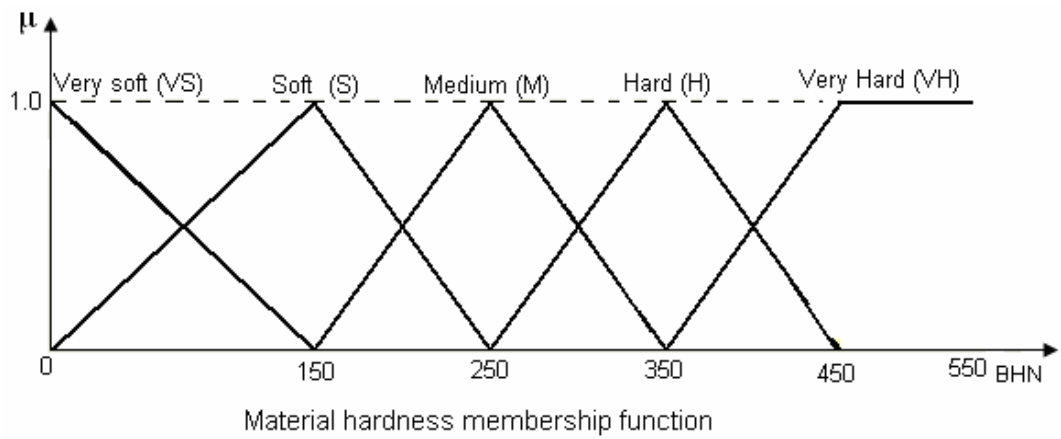
Fuzzy set	Range			Symbol	Fuzzy set	Range			Symbol
	a	B	c			A	b	c	
Input variables									
Material hardness					Hole diameter				
Very soft	0	0	150	VS	Very small	0	0	6	VS
Soft	0	150	250	S	Small	0	6	13	S
Medium	150	250	350	M	Medium	6	13	26.5	M
Hard	250	350	450	H	Large	13	26.5	55	L
Very hard	350	450	550	VH	Very large	26.5	55	80	VL
Depth of cut					Thread pitch				
Very small	0	0	1	VS	Very short	0	0	0.5	VS
Small	0	1	2.5	S	Short	0	0.5	1.5	S
Medium	1	2.5	4	M	Medium	0.5	1.5	2.5	M
Large	2.5	4	6	L	Long	1.5	2.5	3.5	L
Very large	4	6	10	VL	Very long	2.5	3.5	4.5	VL
Output variables									
Cutting speed					Feed rate				
Very low	0	0	15	VL	Very slow	0	0	0.15	VS
Low	0	15	55	L	Slow	0	0.15	0.3	S
Medium	15	55	100	M	Medium	0.15	0.3	0.8	M
High	55	100	160	H	Fast	0.3	0.8	1.2	F
Very High	100	160	250	VH	Very fast	0.8	1.2	1.5	VF

5.5.2 Fuzzy rules knowledge base

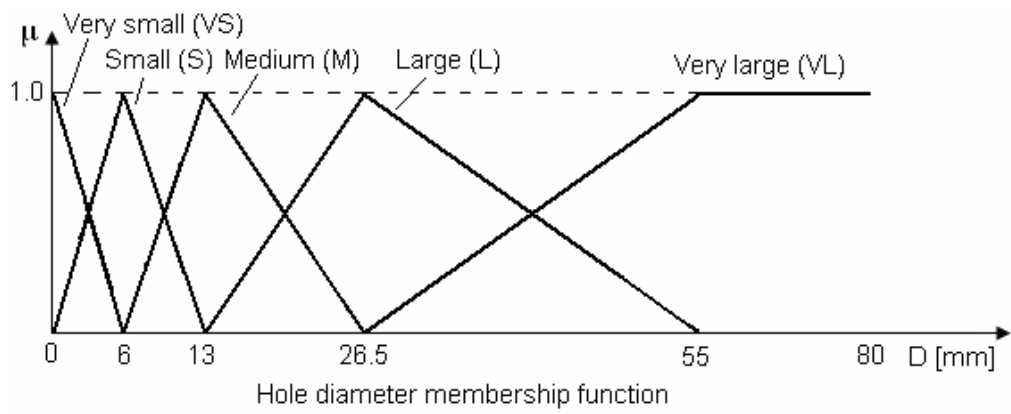
A fuzzy model uses fuzzy rules, which are linguistic IF-THEN statements involving fuzzy sets and fuzzy inference. Fuzzy rules play key role in representing expert modeling knowledge and experience and in linking the input variables of fuzzy models to output variables. The most used type of fuzzy rules is known as Mamdani fuzzy rules (Ying, 2000; Berkan and Sheldon, 1997). A simple but representative Mamdani fuzzy rule describing the selection of cutting speed in drilling operation is given as:

IF Material Hardness is *Soft* **AND** Hole Diameter is *Medium* **THEN** Cutting Speed is *High*.

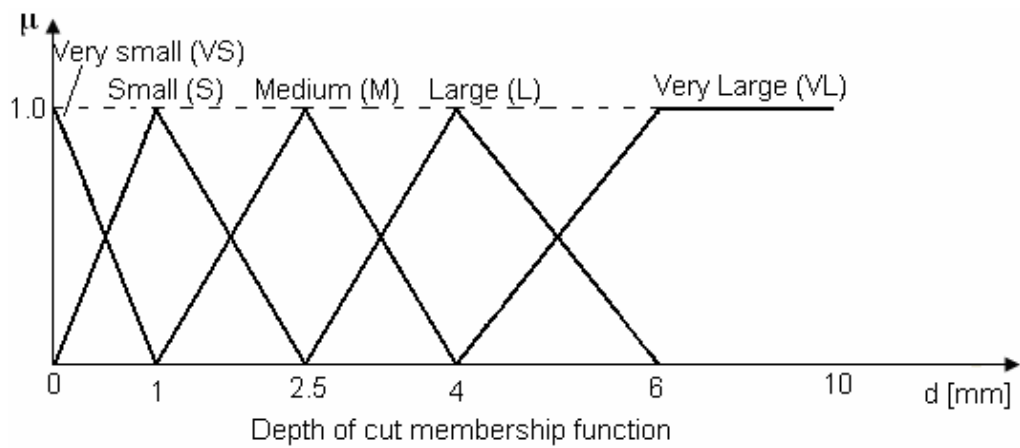
Where material hardness and hole diameter are input variables and cutting speed is output variable. "Soft", "Medium", and "High" are fuzzy sets, and the first two are called input fuzzy sets while the last one is called output fuzzy set. The variables as well as linguistic terms, such as High can be represented by mathematical symbols.



(a)

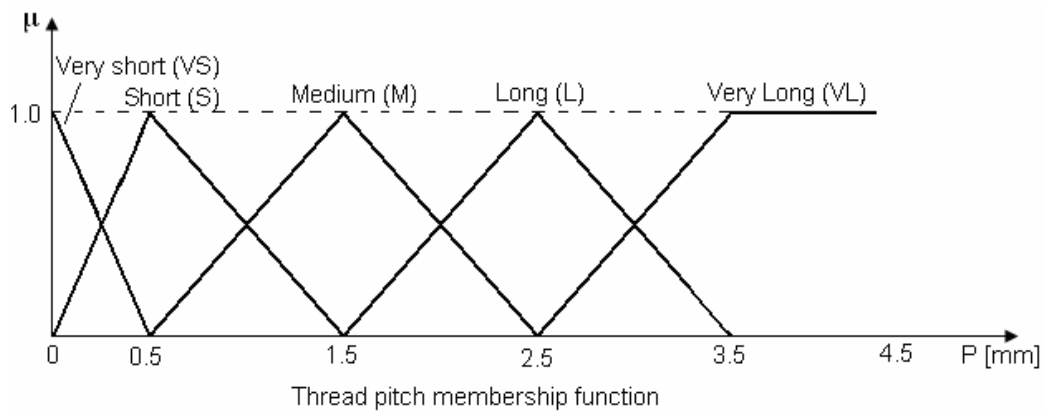


(b)

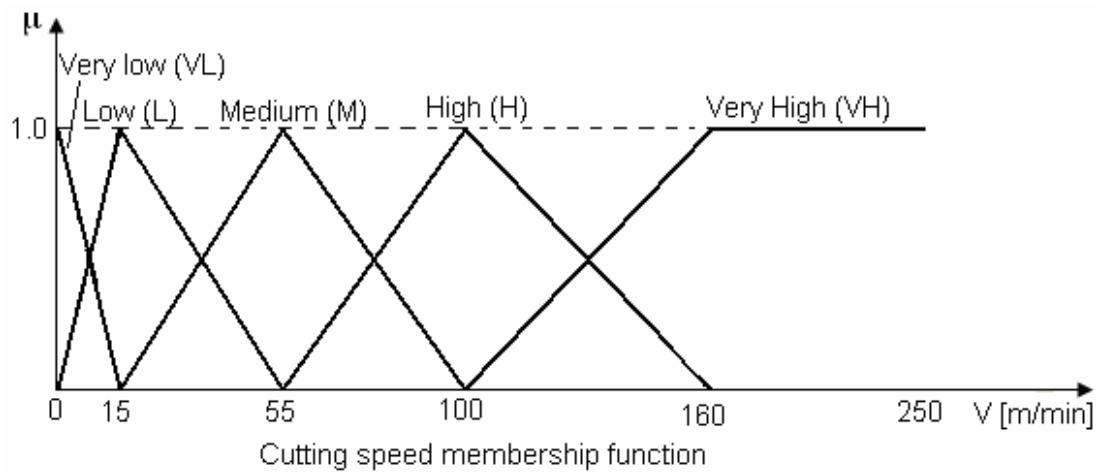


(c)

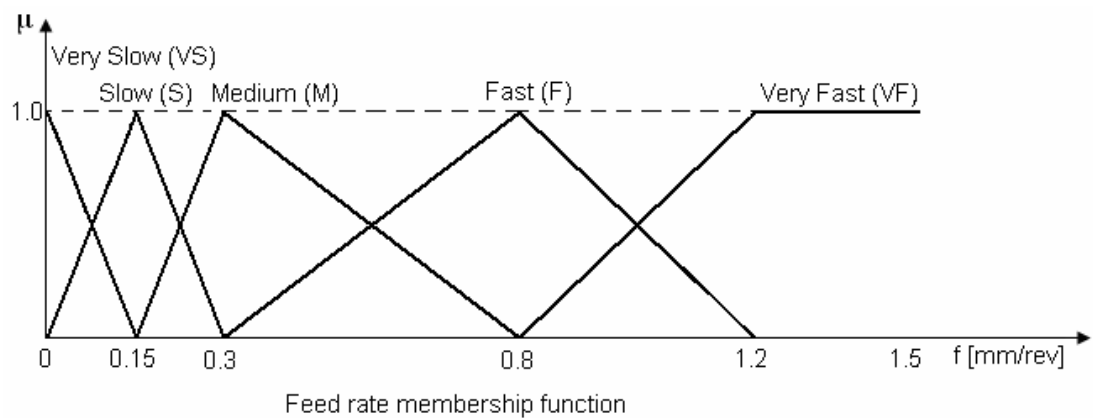
Figure 5.12 Membership functions for input and output variables



(d)



(e)



(f)

Figure 5.12 (Continued) Membership functions for input and output variables

Thus, a Mamdani fuzzy rule for a fuzzy model involving two input variables and two output variables can be described as follows:

IF X_1 is A **AND** X_2 is B **THEN** Y_1 is C, Y_2 is D

Where X_1 and X_2 are input variables, and Y_1 and Y_2 are output variables. A, B, C, and D are fuzzy sets, and AND is a fuzzy logic operator. The IF-part " X_1 is A AND X_2 is B" is called the rule premise, whereas the remaining part, THEN-part " Y_1 is C, Y_2 is D", is called the rule conclusion.

A set of fuzzy rules have been constructed for each fuzzy model, based on the knowledge extracted from machining data handbooks. In this research work, nine fuzzy models have been developed as shown in Table 5.12. Each model can utilize two input variables, two output variables, five fuzzy sets, nine workpiece materials, and two tool materials combinations. With these numbers of parameters, each fuzzy logic model needs a maximum number of rules about 450 rules. Appendix H of this thesis describes these fuzzy rules in a tabulated form. For the purpose of explanation on how these rules are utilized, Table 5.13 shows the fuzzy rules used to select cutting speed and feed rate for twist drilling of carbon steel workpiece with high speed steel tool.

Table 5.12 Summary of developed fuzzy logic models

Fuzzy logic model	Input variables	Output variables
Twist drilling model	Hole diameter Material hardness	Cutting speed Feed rate
Spade drilling model	Hole diameter Material hardness	Cutting speed Feed rate
Center drilling, Counterboring, and countersinking model	Hole diameter Material hardness	Cutting speed Feed rate
Reaming model	Hole diameter Material hardness	Cutting speed Feed rate
Boring model	Depth of cut Material hardness	Cutting speed Feed rate
Tapping model	Thread pitch Material hardness	Cutting speed Feed rate
End milling	Depth of cut Material hardness	Cutting speed Feed rate
Side milling	Depth of cut Material hardness	Cutting speed Feed rate
Plane milling	Depth of cut Material hardness	Cutting speed Feed rate

Table 5.13 Fuzzy rules table for twist drilling carbon steel workpiece with HSS tool

Material Hardness (bhn)		Hole diameter (d)				
		Very small	Small	Medium	Large	Very large
Very soft	V	M	M	M	M	M
	F	VS	S	M	F	F
Soft	V	L	L	L	L	L
	F	VS	S	M	F	F
Medium	V	L	L	L	L	L
	F	VS	S	M	M	V
Hard	V	VL	VL	VL	VL	VL
	F	VS	S	S	M	F
Very hard	V	VL	VL	VL	VL	VL
	F	VS	S	S	M	M

Table 5.13 shows the example of tabulated rules between work material hardness (bhn) and hole diameter (d) and the corresponding cutting speed and feed rate. The first column denotes the fuzzy sets for the workpiece material hardness (VS, S, M, H, VH) starting from very soft to very hard. The first row denotes the fuzzy sets for hole diameter varying from very small to very large (VS, S, M, L, VL). The contents of the table are the outputs yielded, which are the cutting speed (v) and feed rate (f) for this model. The AND used in the rules will apply to the fuzzy AND operation. A few examples of fuzzy rules (from Table 5.13) in a Mamdani form are presented as follows:

- R₁ IF bhn is Very soft AND d is Very small THEN v is Medium, f is Very slow
R₂ IF bhn is Soft AND d is Small THEN v is Medium, f is Very slow
R₃ IF bhn is Soft AND d is Large THEN v is Low, f is Fast

5.5.3 Fuzzy inference

Fuzzy inference is sometimes called fuzzy reasoning. It is used in a fuzzy rule to determine the rule outcome from the given rule input information. Fuzzy rules represent modeling knowledge or experience. When specific information is assigned to input variables in the rule premise, fuzzy inference is needed to calculate the

outcome for output variables in the rule conclusion. In other words, for the general Mamdani fuzzy rule, the question about fuzzy inference is the following: Given $X_i = \alpha_i$, for all of i , where α_i are real numbers, what should Y_i be? For fuzzy modeling, after fuzzifying X_i at α_i and applying fuzzy logic AND operation on the resulting membership values in the fuzzy rule, we attain a combined membership value, μ , which is the outcome for the rule premise. Then, the question is how to compute "Then-part" in the rule. Calculating "THEN" is called *fuzzy inference*. Specifically, the question is: Given μ , how should Y_i be computed? (Ying, 2000).

A number of fuzzy inference methods can be used to accomplish this task. In this research work, the Max-Min inference method is used. In this method, all the fuzzy AND operations are applied into all the input's value of the corresponding fuzzy sets. Applying a fuzzy AND operation will yield a result that is the minimum of the fuzzy value of the number of input variables. The aggregation of the rule will be the truncation of the output fuzzy set. This method is applied to all rules to obtain the final result which gives the final shape of the output fuzzy membership function after aggregation of all the rules, respectively. Then the union operation is applied to all the output fuzzy sets to yield the final fuzzy set (Tsoukalas and Uhrig, 1997)

5.5.4 Defuzzification of output values

Defuzzification is a mathematical process used to convert a fuzzy set or fuzzy sets to a real number. It is necessary step because fuzzy sets generated by fuzzy inference in fuzzy rules must be somehow mathematically combined to come up with one single number as the output of a fuzzy model (Tsoukalas and Uhrig, 1997).

Every fuzzy model uses a defuzzifier, which is simply a mathematical formula, to achieve defuzzification. For fuzzy models with more than one output variable, defuzzification is carried out for each of them separately but in a very similar fashion. In most cases, only one defuzzifier is employed for all output variables,

although it is theoretically possible to use different defuzzifiers for different output variables.

In this research work, the centroid or center of area (COA) is used as a defuzzifier for all output variables of the developed models. In COA defuzzification the crisp value u^* is taken to be the geometrical center of the output fuzzy value $\mu_{out}(u)$, where $\mu_{out}(u)$ is formed by taking the union of all fuzzy rule contributions. The center is the point which splits the area under the $\mu_{out}(u)$ curve into two equal parts. The defuzzified output is defined as

$$u^* = \frac{\sum_{i=1}^N u_i \mu_{out}(u_i)}{\sum_{i=1}^N \mu_{out}(u_i)}$$

Where the summation is carried over (discrete) values of the universe of discourse u_i sampled at N points. COA is a well known and often used defuzzification method (Tsoukalas and Uhrig, 1997).

5.5.5 Fuzzy logic algorithm

In this research work, nine fuzzy models have been developed for selection of machining parameters. Each model utilizes two input variables and two output variables. Each input and output variable is partitioned into five fuzzy regions (sets). A fuzzy rule base for each fuzzy model is generated and saved in separate files. The rule base contains a maximum number of rules about 450 rules for each model. The Max-Min inference method is used as the fuzzy inference engine, and the center of area method is used as a defuzzifier for the output variables. The fuzzy logic algorithm developed in this research work is based on four main steps summarized as follows:

Step 1 *Fuzzification of input values*

1. Fuzzify the input values of X_1, X_2, \dots, X_n variables using the fuzzification formula of triangular membership function:

$$\mu_{FSI_i}(x_j) = \begin{cases} 1 - \frac{|x_j - a_i|}{b_i - a_i} & (a_i \leq x_j \leq b_i) \\ 1 - \frac{|c_i - x_j|}{c_i - b_i} & (b_i \leq x_j \leq c_i) \\ 0 & \text{otherwise} \end{cases}$$

Where

$\mu_{FSI_i}(x_j)$ are the degree of membership value of input variables X_j to the fuzzy set FSI_i .

X_j are the input variables to the fuzzy model ($j = 1, 2, \dots, n$, n = number of input variables).

a_i are the minimum values of the fuzzy set FSI_i .

b_i are the middle values of the fuzzy set FSI_i .

c_i are the maximum values of the fuzzy set FSI_i .

FSI_i are the fuzzy sets associated with the input variables X_j ($i = 1, 2, \dots, m$, m = number of fuzzy sets for X_j variable).

Step 2 *Fuzzy inference*

2. Pass the fuzzified values to the fuzzy rules knowledge base through the inference method used. The evaluation form for possible rules can be written as follows;

IF X_1 is FSI_1 **AND** X_2 is FSI_2 **AND** X_n is FSI_m
THEN Y_1 is FSO_1, Y_2 is FSO_2, \dots, Y_p is FSO_q

Where

Y_j are the output variables of the fuzzy model ($j = 1, 2, \dots, p$, p = number of output variables).

FSO_i are the fuzzy sets associated with the output variables Y_j ($i = 1, 2, \dots, q$, q = number of fuzzy sets for Y_j variable).

- Use the Max-Min inference method (i.e. the min " \wedge " interpretation of AND). The degree of fulfillment of each fired rule can be calculated as follows;

$$DOF_k = \mu_{FSI_1}(x_1) \wedge \mu_{FSI_2}(x_2) \wedge \dots \mu_{FSI_m}(x_n)$$

Where k is the number of fired rules contributed for output variable calculation.

- The fuzzy output $\mu(Y_j)$ is the union (max \vee) of the contributions DOF_k and can be written as follows;

$$\mu(Y_j) = \mu_{FSO_1}(y_1) \vee \mu_{FSO_2}(y_2) \vee \dots \mu_{FSO_m}(y_p)$$

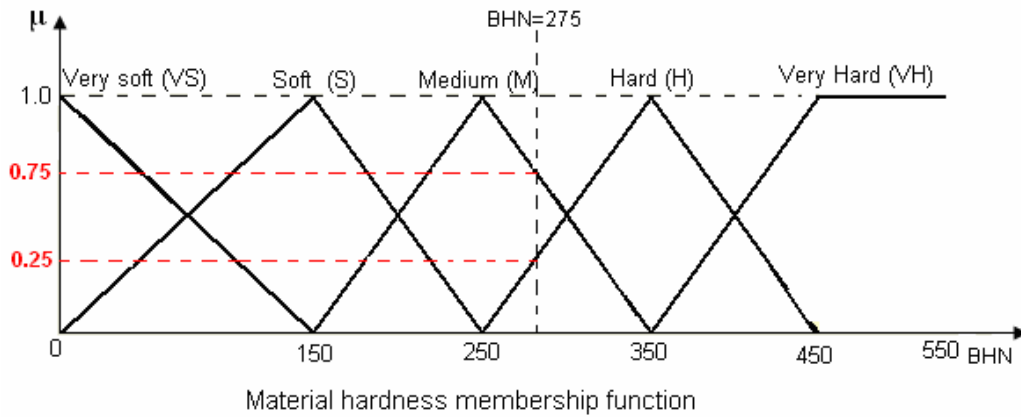
Step 3 *The defuzzification of output values*

- The crisp numbers for Y_1, Y_2, \dots, Y_p can be calculated using the center of area defuzzification method as follows;

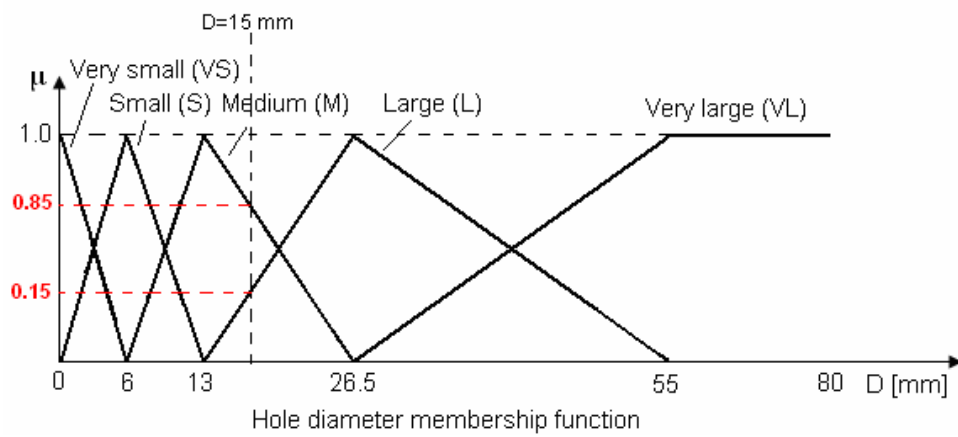
$$Y_j = \frac{\sum Y_j \mu(Y_j)}{\sum \mu(Y_j)}$$

5.5.6 Machining parameters selection example

To demonstrate the application of the proposed fuzzy models, an example is being presented to select cutting speed and feed rate for twist drilling of carbon steel workpiece with high speed steel tool. Consider the situation where work material hardness (bhn) is equal to 275 and hole diameter (d) is equal to 15 mm. Using the fuzzification formula of triangular membership function, the crisp material hardness value of 275 belongs to fuzzy set Medium to a degree of 0.75 and to fuzzy set Hard to degree of 0.25. Similarly, crisp hole diameter value of 15 belongs to fuzzy set Medium to degree of 0.85 and to fuzzy set Large to degree of 0.15, see Figure 5.13.



(a)



(b)

Figure 5.13 Fuzzification of the input values of material hardness and hole diameter

These fuzzified values are then passed to the fuzzy rules knowledge base through the inference method used. The only rules that will have degree of fulfillment, DOF (it is a measure of the degree of similarity between the input and the premise of the rule) greater than zero will fire up. In the case of this example the following four rules will fire up (see Table 5.13).

- R₁ **IF** *bhn* is **M** and *d* is **M** **THEN** *v* is **L**, *f* is **M**
- R₂ **IF** *bhn* is **M** and *d* is **L** **THEN** *v* is **L**, *f* is **M**
- R₃ **IF** *bhn* is **H** and *d* is **M** **THEN** *v* is **VL**, *f* is **S**
- R₄ **IF** *bhn* is **H** and *d* is **L** **THEN** *v* is **VL**, *f* is **M**

Using the Max-Min inference method of DOF (i.e. the min (\wedge) interpretation of AND), each rule contributes the machining parameters values. The degree of fulfillment of each rule can be calculated as follows (see Figure 5.14 for evaluation steps);

$$R_1 \quad \text{DOF}_1 = \mu_{\text{medium}}(275) \wedge \mu_{\text{medium}}(15) = 0.75 \wedge 0.85 = 0.75$$

Contributes Low to cutting speed and Medium to feed rate.

Similarly, rules R_2 , R_3 , and R_4 can written as

$$R_2 \quad \text{DOF}_2 = \mu_{\text{medium}}(275) \wedge \mu_{\text{large}}(15) = 0.75 \wedge 0.15 = 0.15$$

Contributes Low to cutting speed and Medium to feed rate.

$$R_3 \quad \text{DOF}_3 = \mu_{\text{hard}}(275) \wedge \mu_{\text{medium}}(15) = 0.25 \wedge 0.85 = 0.25$$

Contributes Very Low to cutting speed and Slow to feed rate.

$$R_4 \quad \text{DOF}_4 = \mu_{\text{hard}}(275) \wedge \mu_{\text{large}}(15) = 0.25 \wedge 0.15 = 0.15$$

Contributes Very Low to cutting speed and Medium to feed rate.

The fuzzy outputs $\mu(v)$ and $\mu(f)$ are the union (max) of these four contributions for each parameter; that is

$$\begin{aligned} \mu(v) &= \mu_{\text{low}}(v) \vee \mu_{\text{low}}(v) \vee \mu_{\text{verylow}}(v) \vee \mu_{\text{verylow}}(v) \\ \mu(f) &= \mu_{\text{medium}}(f) \vee \mu_{\text{medium}}(f) \vee \mu_{\text{slow}}(f) \vee \mu_{\text{medium}}(f) \end{aligned}$$

Selecting crisp numbers for cutting speed, v^* and feed rate, f^* representative of $\mu(v)$ and $\mu(f)$ is the process of defuzzification. Using COA defuzzification, the crisp outputs of the cutting speed, v^* and feed rate, f^* are obtained as follows;

$$v^* = \frac{\sum v \cdot \mu(v)}{\sum \mu(v)}, \quad f^* = \frac{\sum f \cdot \mu(f)}{\sum \mu(f)}$$

According to the input values of material hardness, BHN = 275 and hole diameter, D=15 mm, it is found that the cutting speed $v^* = 13.56$ m/min and feed rate $f^* = 0.2$ mm/rev.

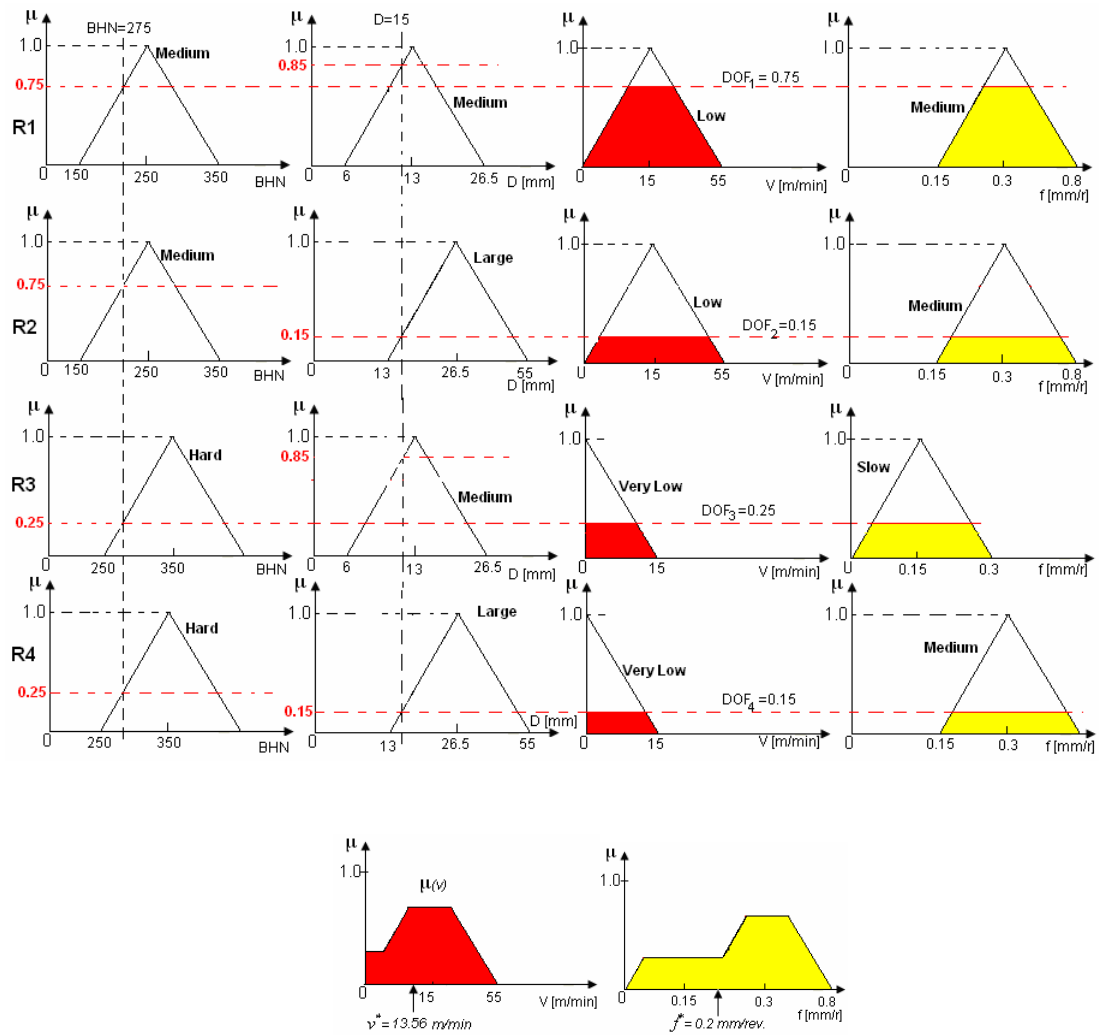


Figure 5.14 Evaluating the fuzzy algorithm of the example

5.6 Application of Rule-based Knowledge in ST-FeatCAPP System.

Setup planning is traditionally done by an experienced process planner. It is a tedious and demanding task in that even for a simple part a setup plan could involve many machines and machining tools, and to generate a feasible setup plan enormous information and tremendous manufacturing knowledge are required (Kim et al., 1996). The manual development of setup plan is very subjective, and setup plans developed this way are generally feasible but far away from optimal. A feasible setup plan is a setup plan which could satisfy fundamental manufacturing constraints, and

following which the part could be machined out of the raw materials and meet design specification (Wu and Chang, 1998; Zhang and Lin, 1999).

The setup planning activity in ST-FeatCAPP is composed of three steps; i.e., setup generation, operation sequence, and setup sequence. The *setup generation* is a procedure to group the machining operations into setups such that the manufacturing features which have common approach directions are grouped into the same setup. The *operation sequence* arranges the machining operations in each generated setup into order, so that the constraint of the feature precedence relationships in each setup is satisfied. In addition, the cutting tool changes among the operations are reduced to a minimum. The *setup sequence* is to arrange the generated setups in order so that setups with less number of machining features are machined first (Ming and Mak, 2000; Contini and Tolio, 2004). A set of rules guiding the setup planning have been used for block base parts and implemented in ST-FeatCAPP system. The following subsection explains the main steps of the implemented algorithm to generate the required setup plans.

5.6.1 Setup planning algorithm

In this research work, feature-based model is used to aid computerizing the algorithm for setup planning. The algorithm is illustrated in the following steps (Ming and Mak, 2000; Tseng, 1998):

Step 1 *generation of setup plans*

1. Define the part coordinate system and assign Tool Access Direction (TAD) for a block shaped part machined on 3-axis milling center (see Figure 5.15). Only one of the six TADs can be set per setup.

TAD₁ defined by (1, 0, 0), +X direction, also named as YZ-left face.

TAD₂ defined by (-1, 0, 0), -X direction, also named as YZ-right face.

TAD₃ defined by (0, 1, 0), +Y direction, also named as XZ-front face.

TAD₄ defined by (0, -1, 0), -Y direction, also named as XZ-back face.
 TAD₅ defined by (0, 0, 1), +Z direction, also named as XY-bottom face.
 TAD₆ defined by (0, 0, -1), -Z direction, also named as XY-top face.

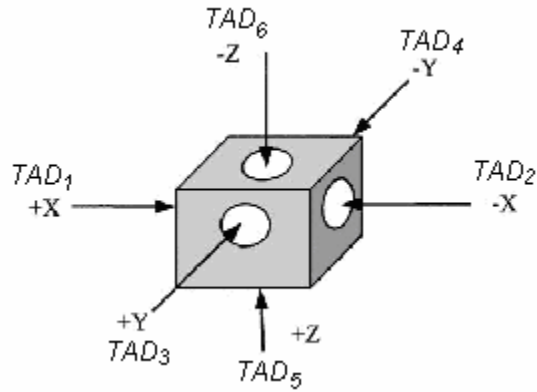


Figure 5.15 Tool access directions

2. Define six setup plans corresponding to each TAD

S_{+x} for TAD₁

S_{-x} for TAD₂

S_{+y} for TAD₃

S_{-y} for TAD₄

S_{+z} for TAD₅

S_{-z} for TAD₆

3. Assign a definite TAD to every feature so that it can be assigned to a definite setup.

Step 2 *Sequence of machining operation in each setup.*

For every setup plan (S_{+x}, S_{-x}, S_{+y}, S_{-y}, S_{+z}, S_{-z}) contains features;

4. Sequence machining operations according to the machining features precedence.

5. Arrange machining operations according to the natural operation sequence (roughing operations prior to finishing operations).
6. Rearrange the drilling type operations according to the following sequence; center drilling + drilling + counterboring or countersinking + tapping + boring or reaming or milling.
7. Minimize the number of tool change by rearranging same type machining operations.

Step 3 *Sequence of setups*

8. Sequence the setup plans so that setups with less machining features are machined first.

5.7 Generation of Digital Process Plans

A preprocessor has been developed to generate a physical STEP-NC process plan file. The main function of this preprocessor is to receive information related to workpiece (features, tolerances, material, etc.) and information produced by process planning (machining operations, cutting tools, machining parameters, etc.) to generate STEP-NC process plan.

5.7.1 STEP-NC process plan structure

STEP-NC, ISO 14649, is basically structure feature-based process plans for manufacturing processes such as milling operations, turning operations, etc., as shown in Figure 5.16. Currently, STEP-NC is developed for milling operation based upon feature information of ISO 10303-AP224. The exchange structure format of STEP-NC adopted by ST-FeatCAPP is based on XML representation (STEP Part 28) and presented as shown in Figure 5.17.

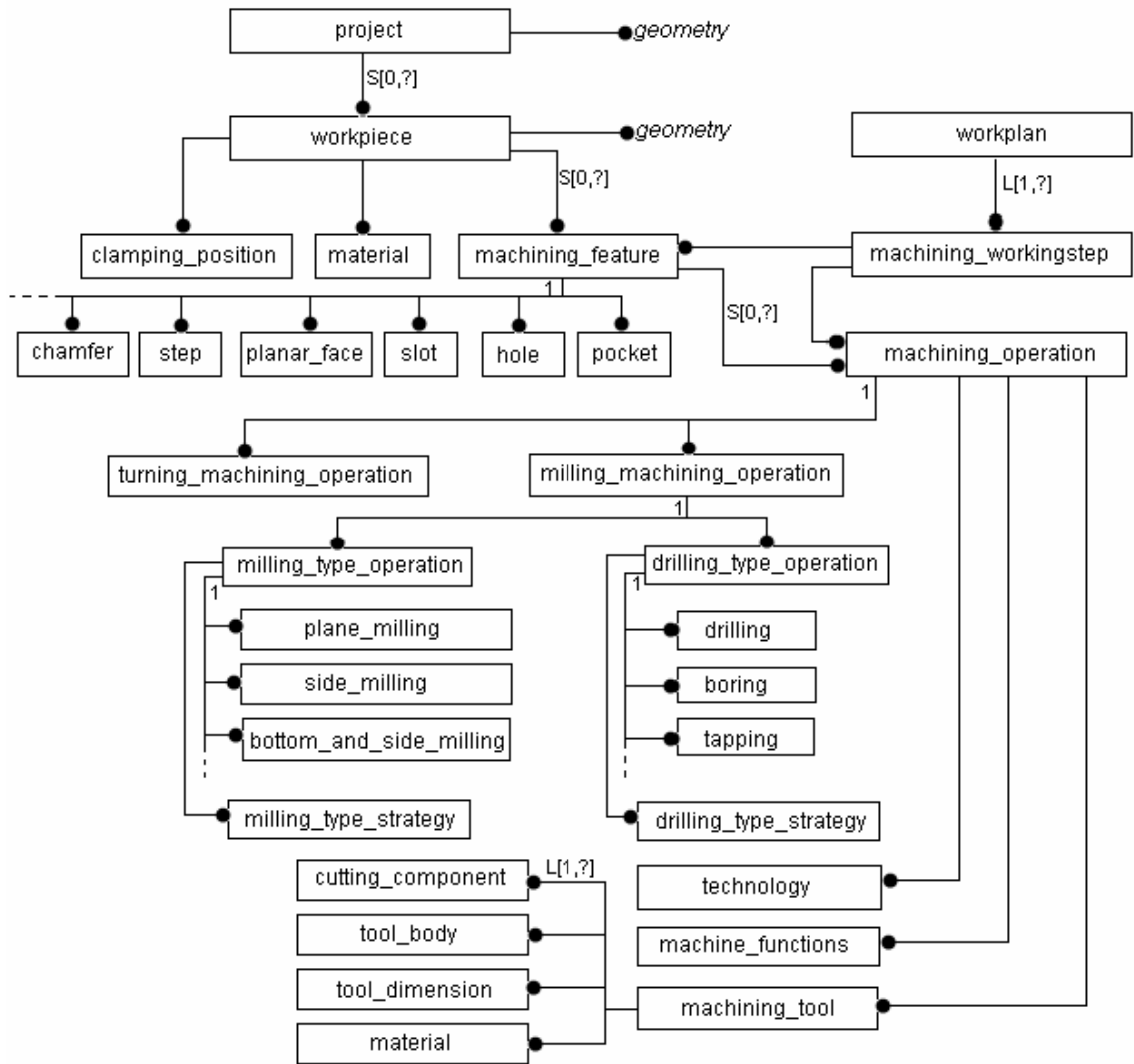


Figure 5.16 Information contents of STEP-NC process plan

Without going into the details, only the most important entities will be covered here to explain the exchange structure of STEP-NC (see ISO 14649 for details). STEP-NC exchange structure consists of four main groups of information that should be sent the CNC machine (Suh et al, 2002; Suh et al, 2003; Allen, et al 2005);

- Task description.
- Part description.
- Tool description.
- Technology description.

As shown in Figure 5.17, each STEP-NC process plan must include exactly one top level entity, called Project. The Project indicates the workplan to be executed upon interpretation of this workplan. The task description is defined in the main workplan attribute, which contains a list of workingstep entities in a linear order. The "its workpieces" attribute of the root entity defines the properties of the workpiece of the project. The workpiece entity contains the entire description of the rough workpiece, if available. This includes material, surface condition and geometric data of the base shape.

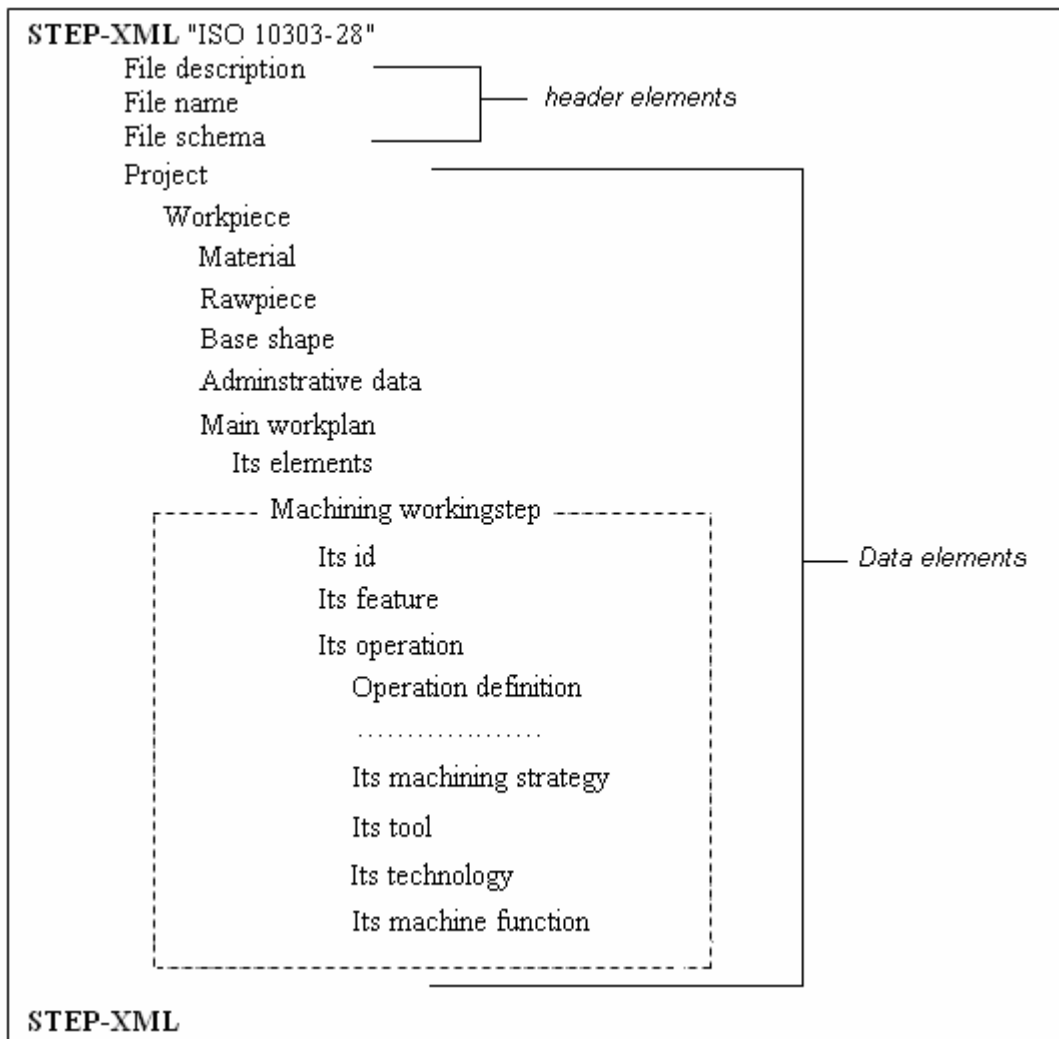


Figure 5.17 Part of STEP-NC structure format generated by ST-FeatCAPP

The *task description item* determines the "how-to-make", the process plan of the part. The process plan is stored in the "its elements" attribute of the workplan

entity. Since this attribute stores a list of workingstep entities. Each workingstep defines the task of a machining operation to be performed on a machining feature. The main workplan attribute of the project entity not only stores the process plan of the part, but also provides an iterator for the features. This way the part description is also obtained.

The *part description item* specifies the "what-to-make", the final shape of the part. In every manufacturing process the part always has a geometric aspect, which defines its final shape. STEP-NC uses machining features to describe the final shape of the part. It actually borrows the features from ISO 10303 AP224, since all the machining features defined in AP224 are redefined in ISO 14649. The difference between the two standards is how this set of features is enumerated. STEP-NC iterates the features in the list of workingsteps, while AP224 defines mating features. The base entity of all features is the "its feature" which is stored in the data as attributes in the machining workingstep entity. The features describe what the machine shall do and the workingsteps and operations describe how the features should be manufactured with specific cutting tool and technological data.

The *tool and technology description items* specify information differs from manufacturing process to manufacturing process. The tool and technology specific information are defined in the attributes of the "its operation" entity which defines the machining operation. The machining operation entity has four attributes defined as follows:

- "its tool" attribute is a machining tool entity, that defines the tool related information.
- "its technology" attribute is a technology entity, that specifies the technology related parameters.
- "its machining strategy" attribute is a machining strategy entity, that specifies the strategy of the manufacturing.
- "its machine functions" attribute is a machine function entity, that indicates the state of various machine functions.

5.7.2 STEP-NC process plan benefits

A multitude of benefits of using STEP-NC process plan have been recognized (Xu, 2004; Suh et al, 2003):

- (a) Because the tasks are easier to define, significant reduction in CAM planning time and data preparation can be achieved.
- (b) There will be significant reduction in number of drawings sent from CAD to CAM, as STEP-NC data is self-documenting.
- (c) Machining time for small to medium sized job lots can be reduced because intelligent optimization can be built into the CNC controller.
- (d) Post-processors will be eliminated because the interface does not require machine-specific information.
- (e) Machine tools are safer and more adaptable because STEP-NC is independent from the machine tool vendor.
- (f) STEP-NC provides a complete and structured data model, linked with geometric and technological information, so that no information is lost between the different stages of the process.
- (g) Modification at the shop floor can be saved and fed back to the design department hence bi-directional information flow from CAD/CAM to NC is achieved.
- (h) XML files can be used for information transfer hence enable Web based manufacturing or e-manufacturing.
- (i) STEP-NC process plan 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 the feature to be machined, type of tools used and the operations to perform (Newman et al, 2002).

CHAPTER 6

DEVELOPED SOFTWARE

6.1 Object-oriented approach

The use of an object-oriented approach is adopted in developing the integrated CAD/CAPP system software. It was chosen since it represents a logical means for representing real-world objects like machined parts (Chep and Tricarico, 1999; Sormaz and Khoshnevis, 1997). Compared with traditional approaches to the design and implementation of software systems, this approach offers advantages of increased flexibility, incremental system development and reusability.

In object-oriented modeling, any real world entity is modeled as an object. Every object has a state and behavior. The state of an object is a set of properties (also called instance variables) of the object, and the behavior of an object is a set of operations (also called methods). These operations are analogous to procedures and functions in conventional programming languages. The process of invoking an operation is called sending a message to the object. Such a message contains arguments just like a procedure or function call in a conventional programming language. Sending message to an object (invocation of an operation) usually modifies the state (properties) of that object (Britton and Doake, 2000).

The conventional object-oriented approach includes data abstraction, classes, encapsulation and inheritance. The following is a brief description to these items (Britton and Doake, 2000; Champeaux et al, 1993; Eliens, 1995).

- *Data abstraction* is the capability to define data structures composed of a variety of data types. It is a model that encompasses a set of data and an associated set of operations that can be performed on the data.
- A *class* is analogous to an abstract data type. All the objects that share the same set of properties and operations are grouped in a class. A class groups all objects which share the same state and behavior. Objects that belong to a class are called instances of that class. An instance object must belong to only one class. A class describes the properties and implements the operations applicable to its instances. Thus, when a message is sent to an instance, the operation which implements the message is found in the definition of the class. The properties of an object can be an object which belongs to some class.
- *Encapsulation* is equivalent to the concept of information hiding in software. The concept states that modules encapsulate or hide information for both operations and data. As mentioned before, an object is a module that contains both operations (code) and properties (persistent data). The state and behavior encapsulated in an object are not visible from outside the object. Operations on objects must use a public interface and occur by sending message to an object. Objects can communicate with each other only through messages which constitute public interface of an object. For each message understood by an object, there is a corresponding operation that executes the message. The binding of underlying data with an associated set of operations that can be used to manipulate the data is called encapsulation. An operation can be simply printing out data, or it can be a complex algorithm.
- *Inheritance* provides explicit support of reusable code and data. Refining an inherited operation adds new functionality to existing code. A new class may be defined as a specification of an existing class; the new class (subclass) inherits desired properties and operations of the existing class (superclass); and the user may specify additional properties and operations for the new class. A class may have any number of subclasses. Some systems allow a

class to have only one direct superclass, called single inheritance, while others allow a class to have any number of direct superclasses, called multiple inheritances.

This research work applies the object-oriented approach to construct the product data model and corresponding design and process planning functions models. The object-oriented programming language, Microsoft Visual BASIC; the unified modeling language, UML; EXPRESS descriptive language; and dynamic library link, DLL, are used to implement the proposed data model and process planning functions.

The data model implemented in this research is based on the application objects defined within STEP AP224 (ISO 10303-224) and STEP-NC (ISO 14649). These objects cover information related to: manufacturing features, tolerances, technological attributes, part administrative data, machining operations, cutting tools, etc. Each application object is programmed in a class file with its public properties and operations (Ming and Mak, 1998). The inheritance feature of object-oriented approach is used to define other common properties and to interface with the operations required to be performed on the instanced objects (Usher, 1996; Luo, 1997).

Figure 6.1 shows the developed system data model represented in terms of the object-oriented approach. The model shown describes the overall relationship between the application objects implemented in this research. Appendix E presents the contents of this model in UML diagrams. Each object has a class diagram titled by its name and contains the properties required to define that object and the operations to be performed.

Unified Modeling Language (UML) is used in the analysis of the developed system. It is a language for specifying, visualizing, constructing, and documenting the artifacts of the software systems. UML is a most important tool for object-oriented analysis and software design. It is not a programming language but a

modeling language. There are various tool kits can automatically generate the programming code from UML representation. In UML-based data model representation, both private and public data can be presented by UML class diagrams. The UML class diagram can explicitly represent the relationships between objects. Hence, the data model, even the complex one, can be well modeled by the UML manner (Stevens and Pooley, 1999; Oh et al, 2001).

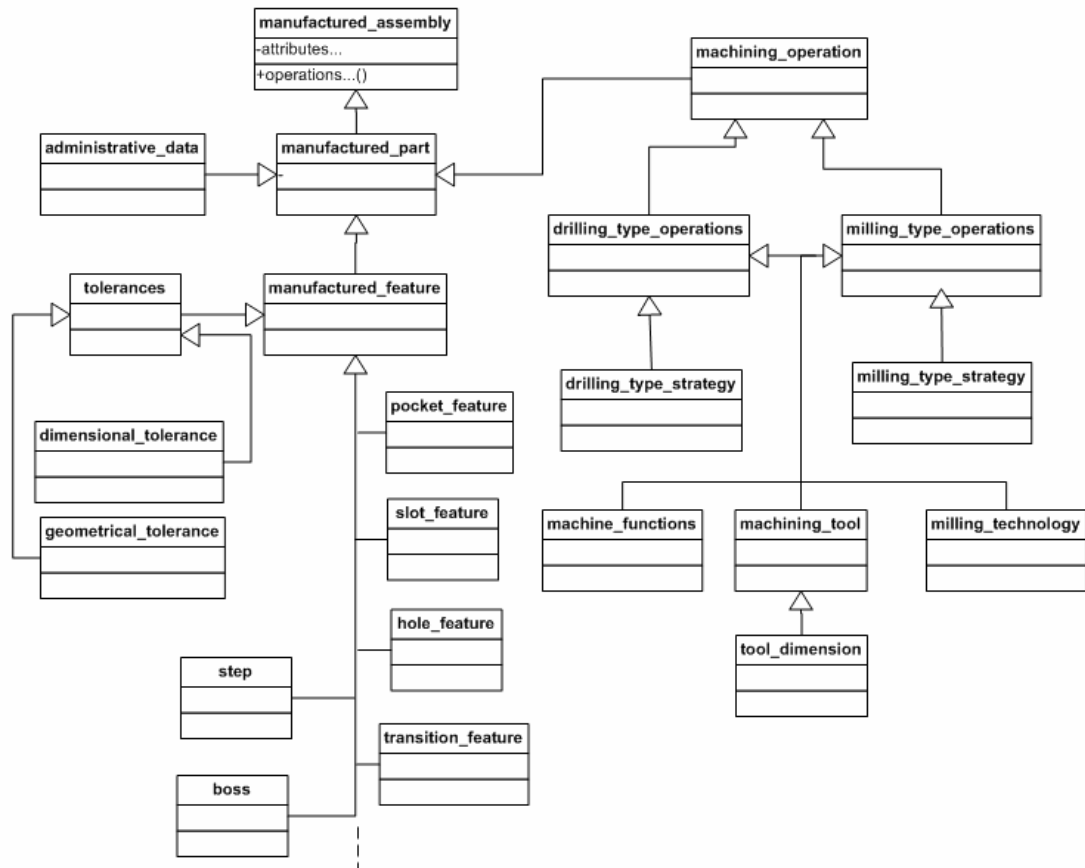


Figure 6.1 Object-oriented approach for a data model

6.2 System implementation

This section discusses the implementation of the STEP-based feature modeler and the feature-based intelligent process planning systems. The implemented systems are named; STEP-FM, an acronym for STEP-Feature Modeler, and ST-FeatCAPP, an acronym for STEP Feature-based process planning. Figure 6.2 shows the

architecture of the two systems in an integrated environment with AutoCAD. The integrated environment of the developed system consists of the following: (1) AutoCAD, (2) STEP-FM, (3) ST-FeatCAPP, (4) STEP features dlls, (5) STEP XML data files, and (6) user interface. AutoCAD is used as an integrator (container) environment of the developed systems. The advantage of using AutoCAD is that it includes a complete Activex automation interface with functions or methods that can be called from visual BASIC. Furthermore, AutoCAD shares the same solid modeling engine as several other CAD systems. It is expected that procedures developed in this research will be extendable to the CAD environment used in many research institutions and industrial establishments.

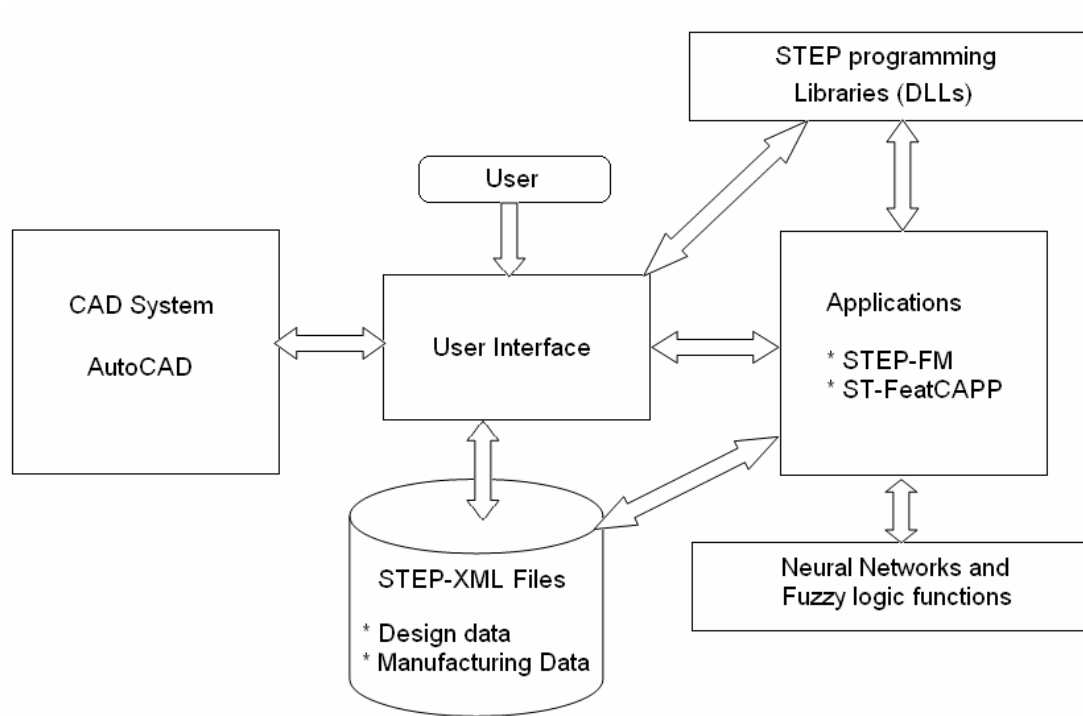


Figure 6.2 System architecture

Activex automation interface provides a mechanism to manipulate AutoCAD programmatically from within or outside AutoCAD. It does this by exposing AutoCAD objects to the "outside world", once these objects are exposed, they can be accessed by many different programming languages. An AutoCAD object is the main building block of any Activex application. Each exposed object represents a

precise part of AutoCAD. There are two advantages to implementing an Activex interface for AutoCAD: (1) programmatic access to AutoCAD drawings is opened up to many more programming environments and (2) sharing data with other MS-Windows applications is made dramatically easier (Clark, 2002; Guenther, 1995).

The user interface has been developed using Visual BASIC for Application (VBA). Microsoft VBA is an object-oriented programming environment designed to provide rich development capabilities similar to those of Visual BASIC (VB). The main difference between VBA and VB is that VBA runs in the same process space as AutoCAD, providing an AutoCAD-intelligent and very fast programming environment. VBA sends messages to AutoCAD by the AutoCAD Activex automation interface. AutoCAD VBA permits the VBA environment to run simultaneously with AutoCAD. This coupling of AutoCAD, Activex automation, and VBA provides an extremely powerful interface not only for manipulating AutoCAD objects, but for sending data to or retrieving data from other applications (Clark, 2002; Guenther, 1995).

There are three fundamental elements that define Activex and VBA programming in AutoCAD. The first is AutoCAD itself, which has a rich set of objects that encapsulates AutoCAD entities, data, and commands. The second element is the AutoCAD Activex automation interface, which establishes messages (communication) with AutoCAD objects. The third element is the VBA programming environment which has its own set of objects, keywords, constants, and so forth that provides program flow, control, debugging, and execution (Clark, 2002; Guenther, 1995).

6.3 Installation and System Requirements

ST-FeatCAPP software installation media (CD-ROM enclosed with this thesis) contains ST-FeatCAPP programs, data files, documentations and sample models. The installation is simply done by inserting the enclosed CD-ROM disk into the

CD_ROM drive. The setup program will automatically launch once the computer detects the CD. The setup instructions are then followed to finalize the installation process.

ST-FeatCAPP installation creates a main installation folder whose name and location can be specified during the installation process (it is recommended to use the default name and location "C:\ST-FeatCAPP"). This folder contains the executable, OCX, and DLL files required to run the system. There are also several subfolders in the installation folder:

- Cutting tools folder contains tool library files in text and MS-Excel formats.
- Fuzzy logic data folder contains the data files needed to utilize the fuzzy rules implemented in the system.
- Help folder contains help files in PDF and MS-Word formats which can be viewed directly from this folder.
- Neural networks folder contains the data files of the implemented neural networks. Input, target, weight, and error data files are placed in this folder.
- Samples folder contains various sample files that can be displayed on ST-FeatCAPP system. These sample files are saved in several formats including AutoCAD drawing format (DWG), ST-FeatCAPP format (STF), Drawing exchange format (DXF), and STEP extendable format (XML).
- Documentation folder contains the standard documents and other related materials used in the development of the ST-FeatCAPP system.

6.3.1 System requirements

ST-FeatCAPP is an ActiveX interface application that runs inside of AutoCAD. It replaces AutoCAD pull-down menus and toolbars with ones used by ST-FeatCAPP. Not all versions of AutoCAD are supported. AutoCAD 2002, Mechanical desktop 6 or previous versions are supported. Later versions of ST-FeatCAPP may support additional versions of AutoCAD and Mechanical desktop.

Hardware requirements imposed on AutoCAD by ST-FeatCAPP are virtually negligible. User can refer to the hardware requirements for 3D modeling in AutoCAD as published by Autodesk for a general guide. ST-FeatCAPP will enable users to create much faster and complex models than is possible with AutoCAD alone. In addition, high-level design and manufacturing information can be displayed at any time of the modeling process. For this reason, it is recommended adding as much system memory (RAM) to the computer as possible, and increasing the system's virtual memory as much as possible through the system applet of the Windows control panel. For maximum performance, a video card with a true color open-GL support is recommended.

6.4 Running STEP-FM/ST-FeatCAPP

Running ST-FeatCAPP is the same as any Windows-based program. It can be run from the programs of the Start button or from a shortcut on the desktop. When ST-FeatCAPP starts, the starting window is displayed (Figure 6.3). This window provides the user with several options to start the modeling process. From this window the user can start with;

- Create a new model.
- Open an existing model.
- Import STEP-AP224 XML file.
- Train implemented neural networks.
- Update fuzzy logic knowledge-base.
- View ST-FeatCAPP help.

6.4.1 User interface

ST-FeatCAPP system adheres to the Windows standard for user interface design. All functions can be accessed from the pull-down menus, and common

functions are accessible via toolbar icons. Figure 6.4 shows the ST-FeatCAPP user interface window. It consists of several pull-down menus and toolbars, modeling space, and AutoCAD command line to take advantages of the existing CAD system. The menus and toolbars of ST-FeatCAPP user interface are described in more details in Appendix J.

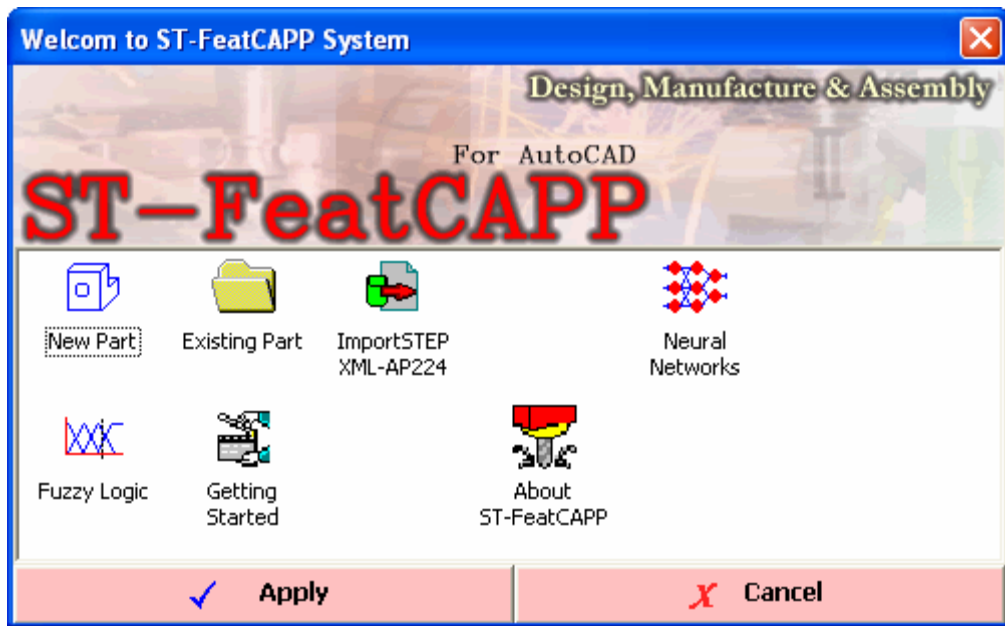


Figure 6.3 ST-FeatCAPP starting window

6.5 Design Example with STEP-FM

To demonstrate the application of the developed feature modeler, an example is presented in this section to illustrate the modeling process of STEP-FM. The following paragraphs and figures present the step-by-step modeling processes of a simple block-base shape part.

When ST-FeatCAPP starts, the starting window is displayed as shown in Figure 6.3. The "New Part" option is selected by double-clicking on the new part icon to start a new part model. The part library window will be displayed as shown in Figure 6.5. Several part base shapes are supported by the developed system. In this example, a block base shape is selected by double-clicking on the block part icon.

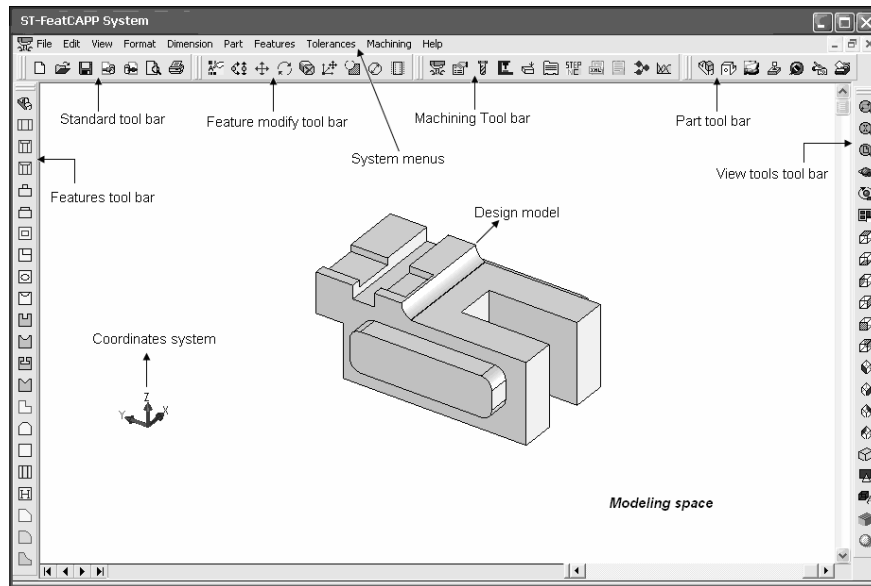


Figure 6.4 ST-FeatCAPP user interface window

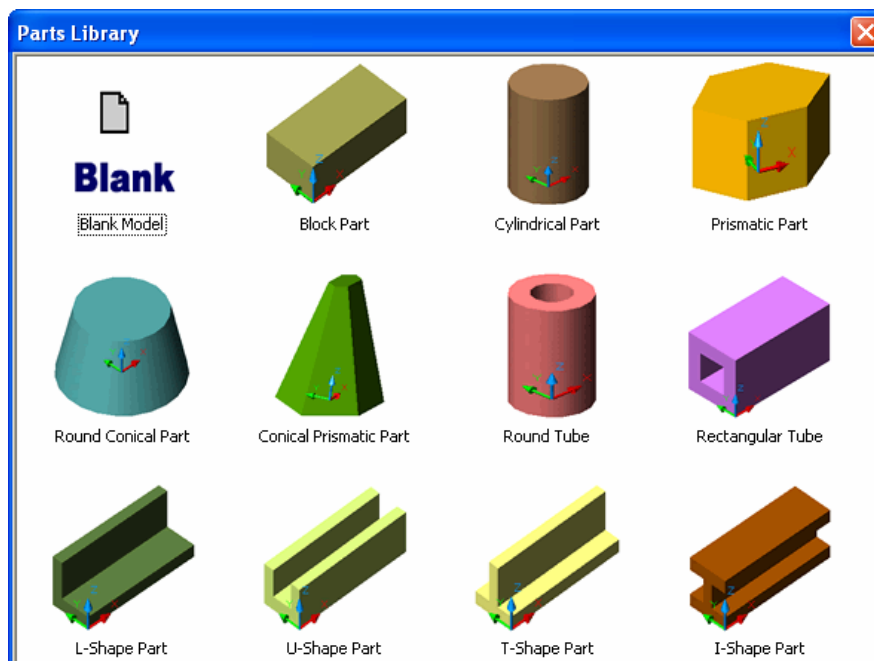


Figure 6.5 Part base shape selection window

The block base shape window will be displayed as shown in Figure 6.6. The part size (length, width, and height), location, and name need to be defined in this window and by pressing "OK" button the base shape will be created. This shape is considered as the starting raw material for modeling the part.

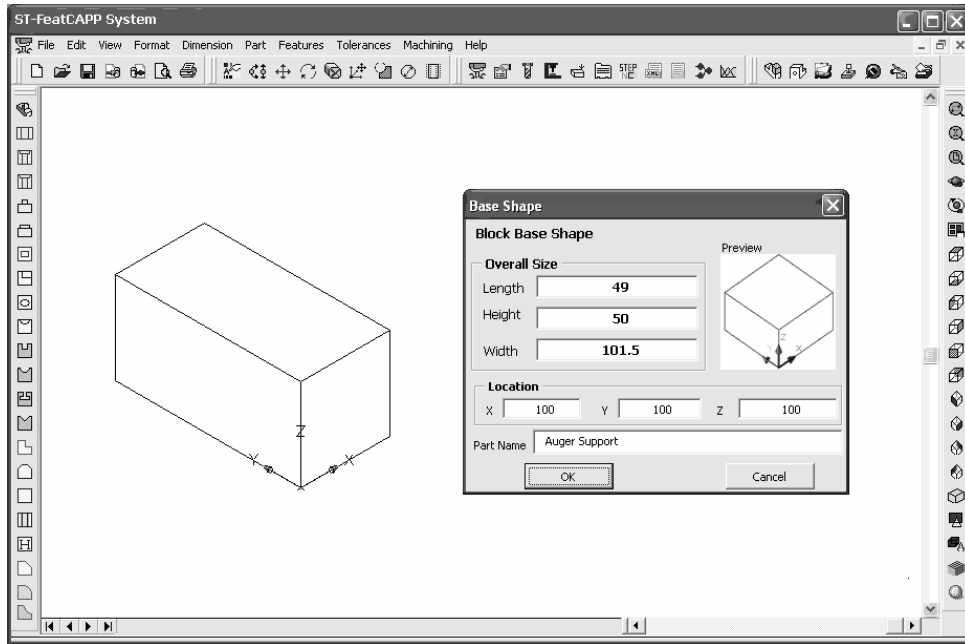


Figure 6.6 block base shape window

After creating the base part, features attachment processes can be started. The designer can start with any feature depends on his/her design for manufacturing intent. In this example, the step feature (ST1) is attached by clicking the step feature icon from the feature toolbar and then defining step attributes (Figure 6.7)

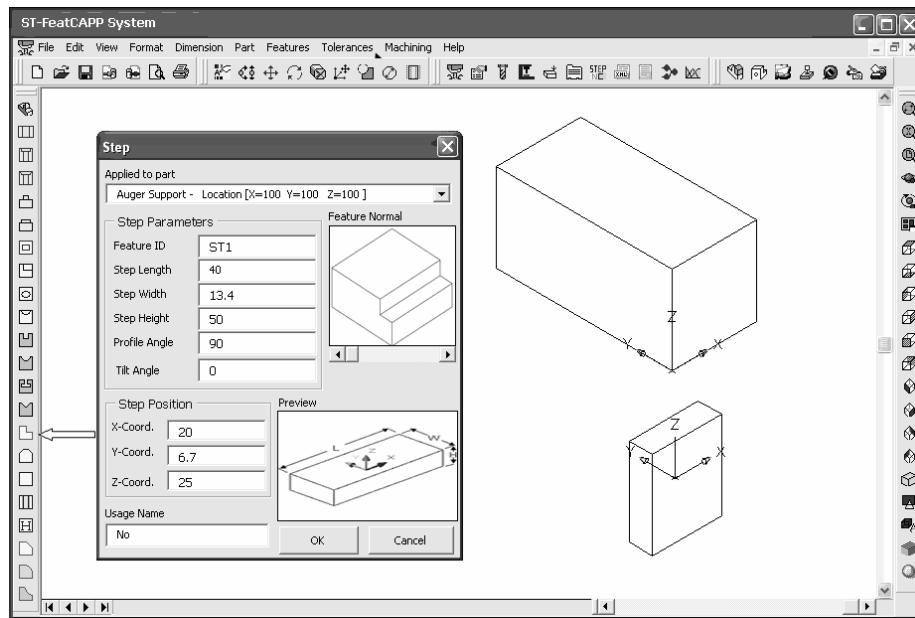


Figure 6.7 Step feature (ST1) attachment process window

From the Boolean operation window, the step feature is subtracted from the main part and the model is regenerated as shown in Figure 6.8.

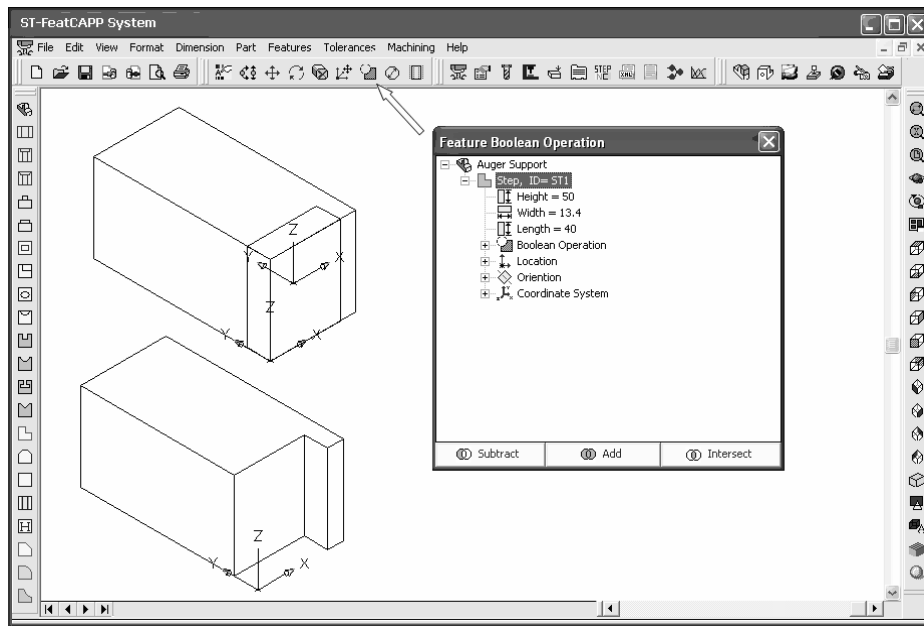


Figure 6.8 Step feature (ST1) subtraction process window

Figure 6.9 shows the attachment process of the step feature (ST2) and the resulted intermediate part form the subtraction operation.

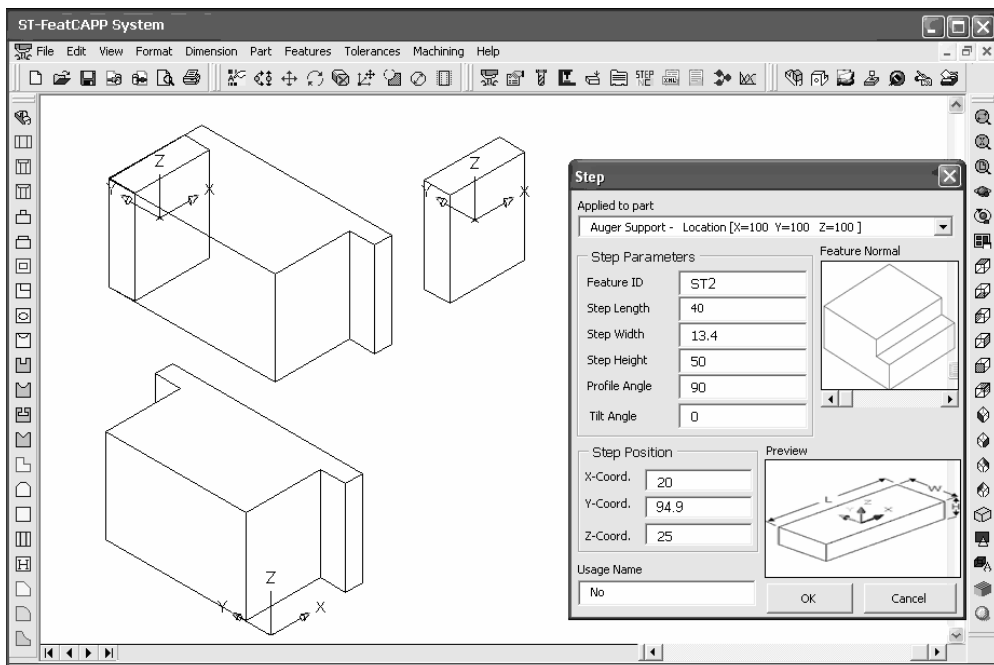


Figure 6.9 Step feature (ST2) attachment process window

Figure 6.10 shows the attachment process of the step feature (ST3) and the resulted intermediate part form the subtraction operation.

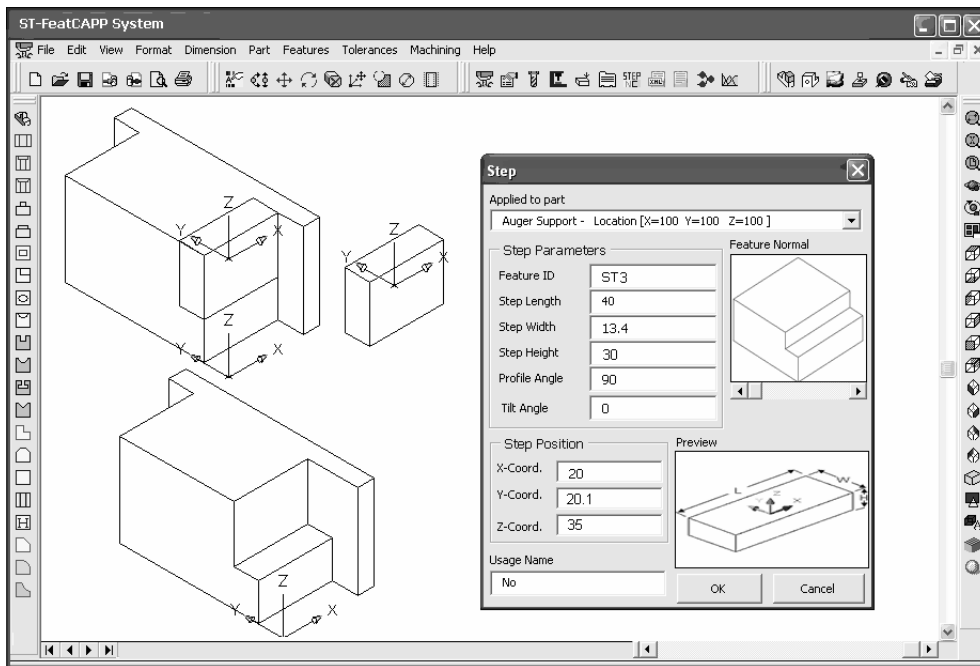


Figure 6.10 Step feature (ST3) attachment process window

Figure 6.11 shows the attachment process of the step feature (ST4) and the resulted intermediate part form the subtraction operation.

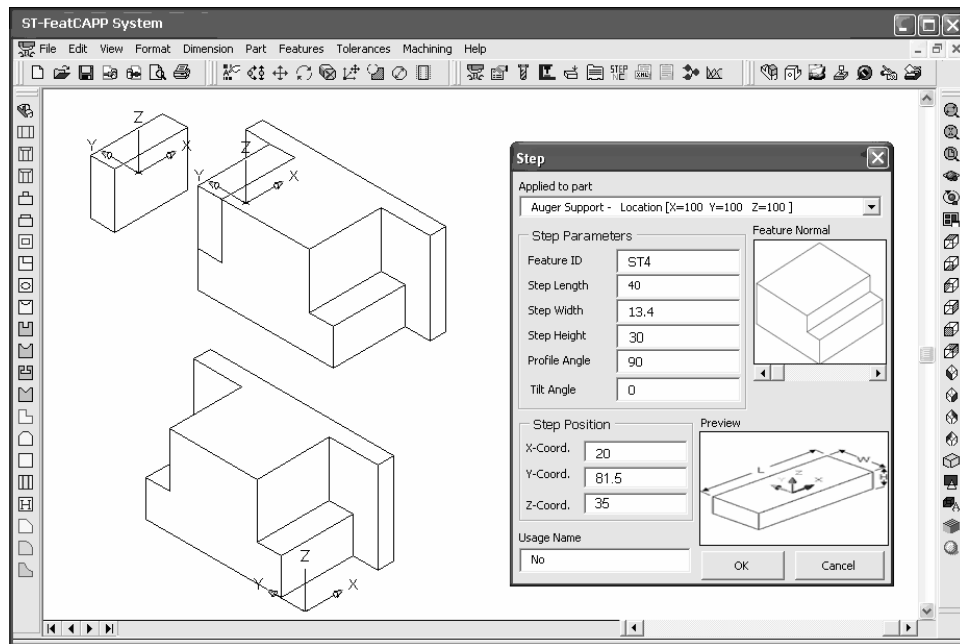


Figure 6.11 Step feature (ST4) attachment process window

Figure 6.12 shows the attachment process of the step feature (ST5) and the resulted intermediate part form the subtraction operation.

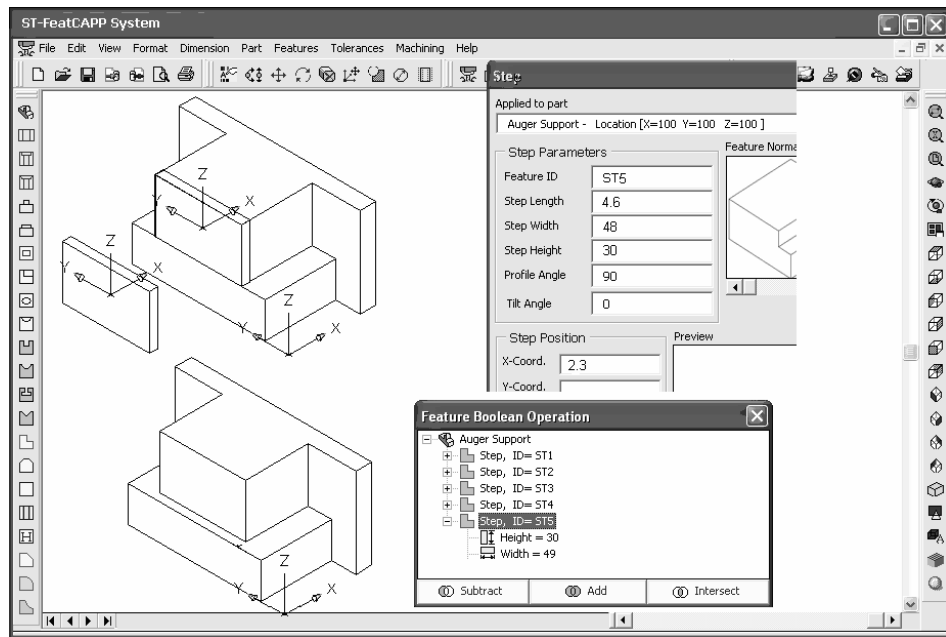


Figure 6.12 Step feature (ST5) attachment process window

The round slot feature (RS1) is attached to the main part at specified feature location. The slot attributes and end conditions are defined and the resulted feature is subtracted from the main part as shown in Figure 6.13

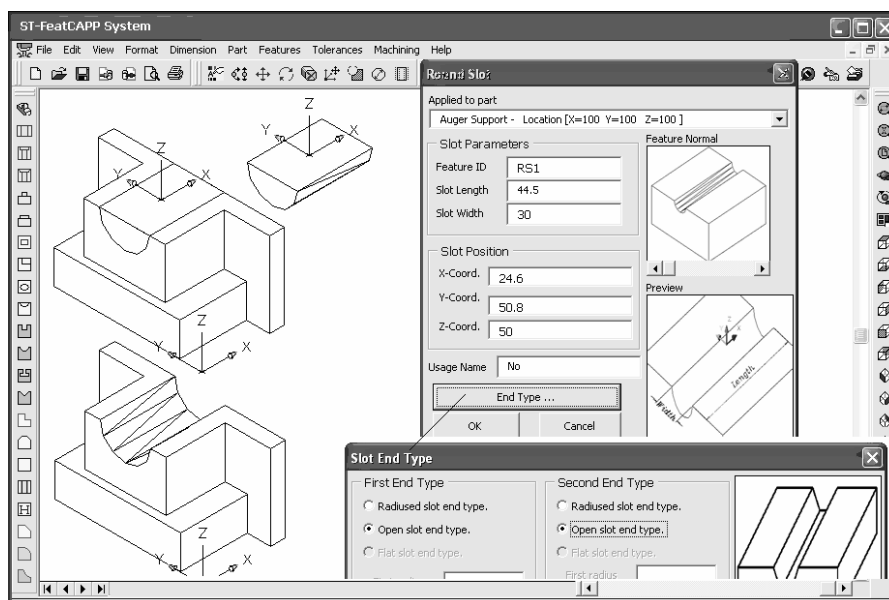


Figure 6.13 Round slot feature (RS1) attachment process window

Figure 6.14 shows the attachment of the edge round feature (ER1) to the part being designed and the resulted intermediate part.

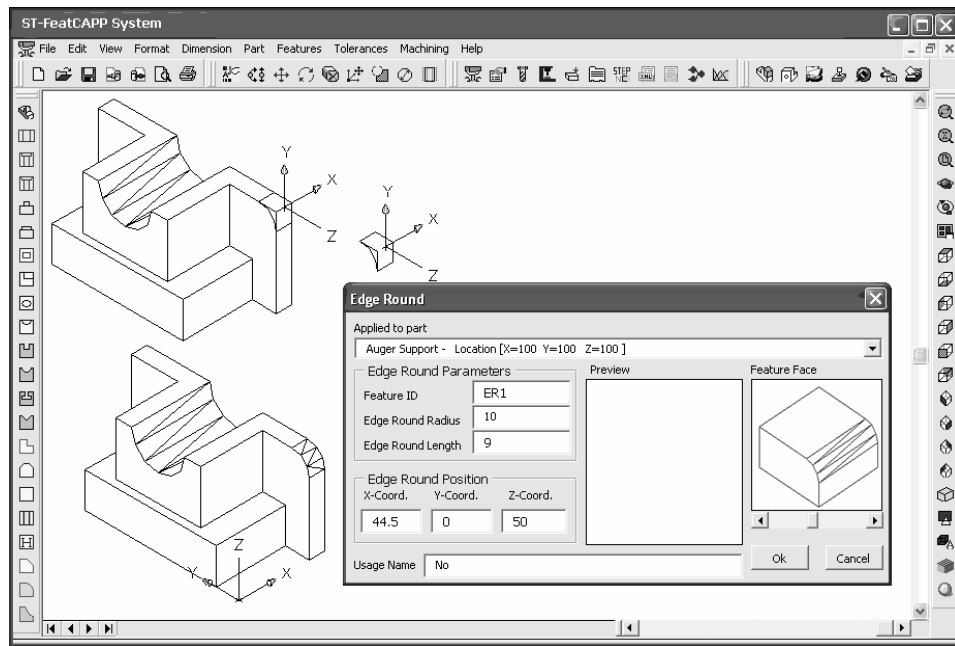


Figure 6.14 Edge round feature (ER1) attachment process window

Figure 6.15 shows the attachment of the edge round feature (ER2) to the part being designed and the resulted intermediate part.

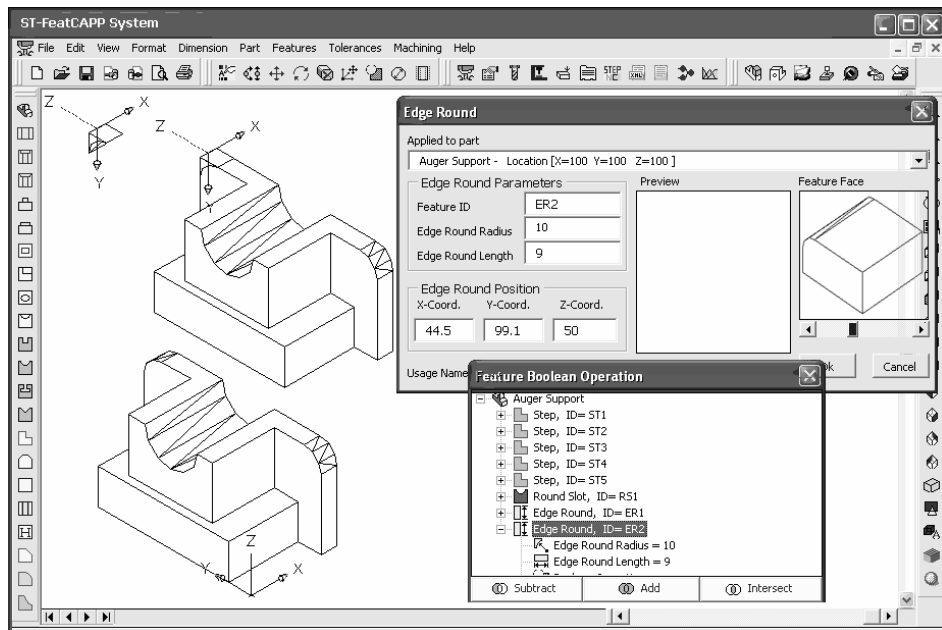


Figure 6.15 Edge round feature (ER2) attachment process window

Figure 6.16 shows the attachment of the round hole feature (RH1) to the part being designed and the resulted intermediate part. The feature is located and oriented in the YZ-plane of the part.

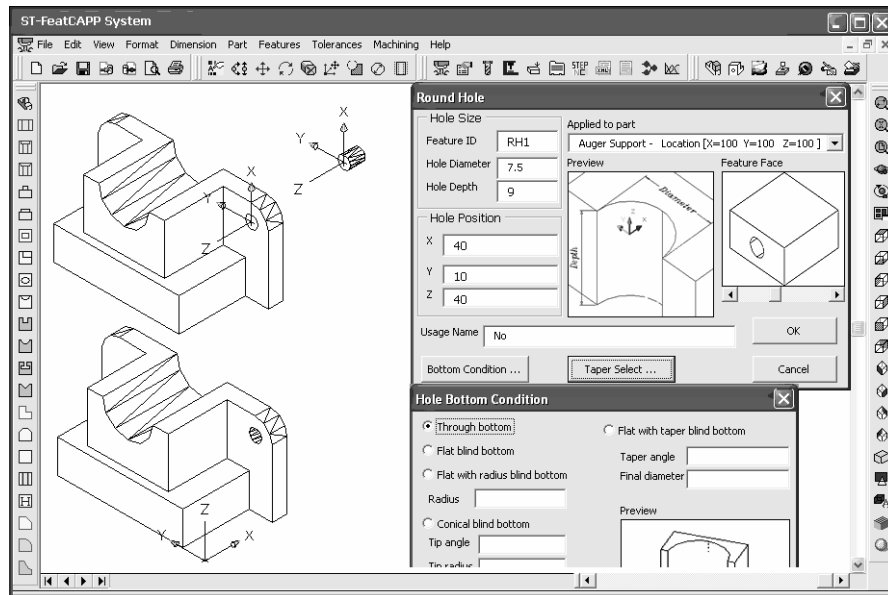


Figure 6.16 Round hole feature (RH1) attachment process window

Figure 6.17 shows the attachment of the second round hole feature (RH2) to the part being designed and the resulted intermediate part.

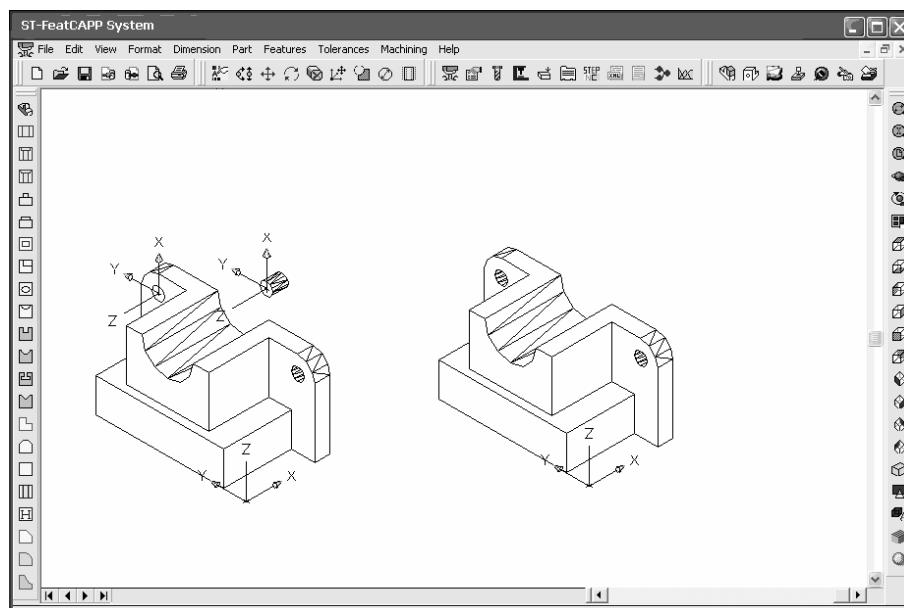


Figure 6.17 Round hole feature (RH2) attachment process window

The last feature which is square slot feature (SQS1) is attached at the bottom of the part (YX-plane). The resulted intermediate part is the final shape of the part modeling process (Figure 6.18).

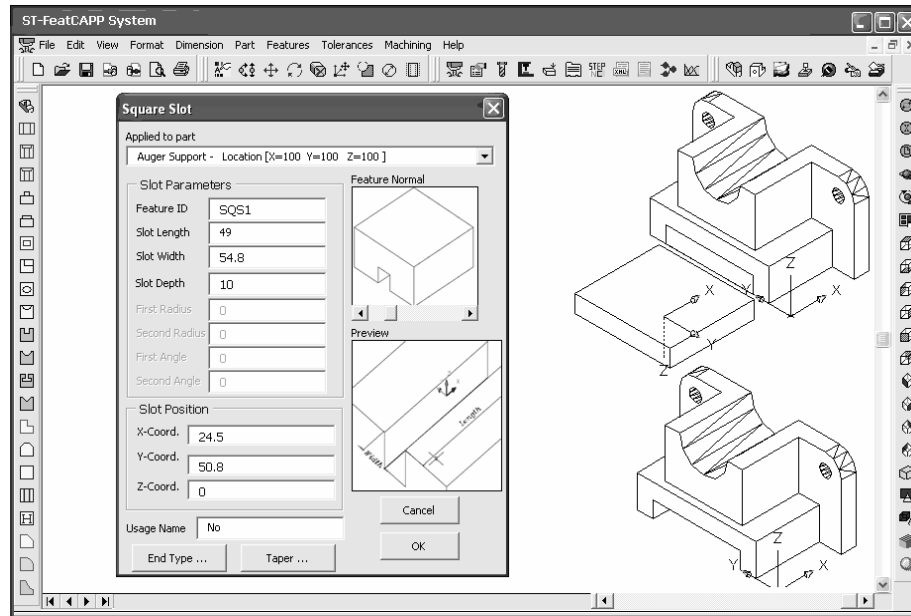


Figure 6.18 Square slot feature (SQS1) attachment process window

Figure 6.19 shows isometric, top, front, and side views of the final shape of the part. At this stage of the modeling process, the designer can assign tolerances, surface finishes, and other technical attributes to the attached features of the part.

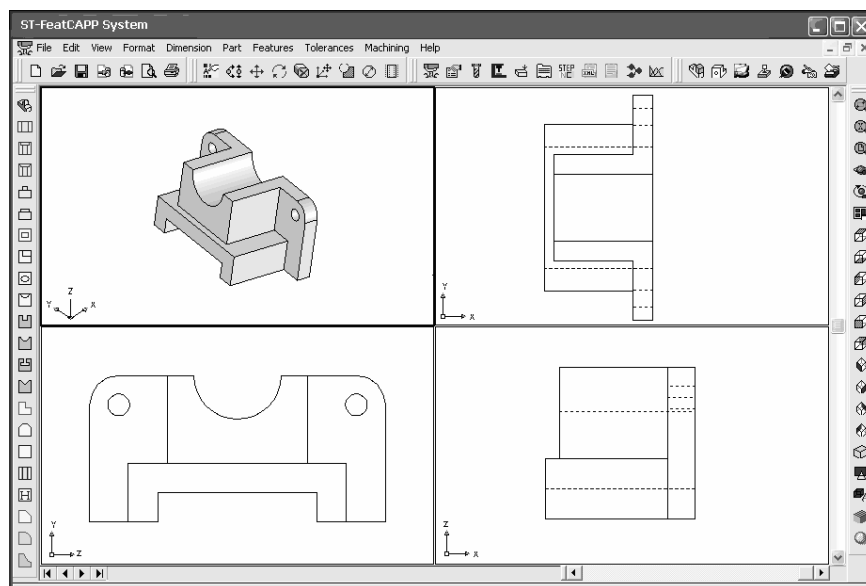


Figure 6.19 Different views of the final part window

To track the feature properties which are attached to the part, feature properties window can be displayed as shown in Figure 6.20.

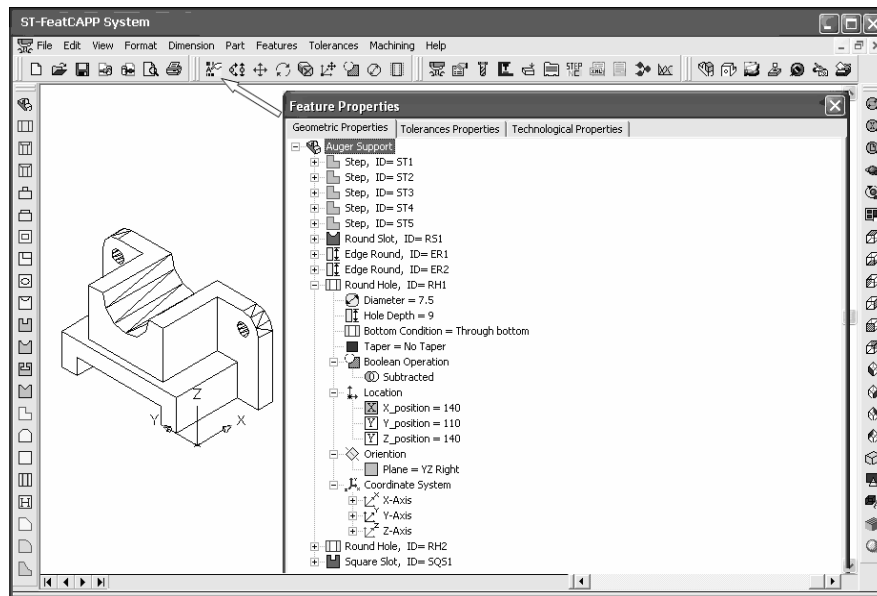


Figure 6.20 Displaying feature properties window

The attachment of dimensional tolerance involves selecting the dimensional tolerance type, defining the tolerance values and attributes, and selecting the feature to which this tolerance is being applied. Figure 6.21 shows the attachment of the diameter dimension tolerance to the round hole feature (RH1).

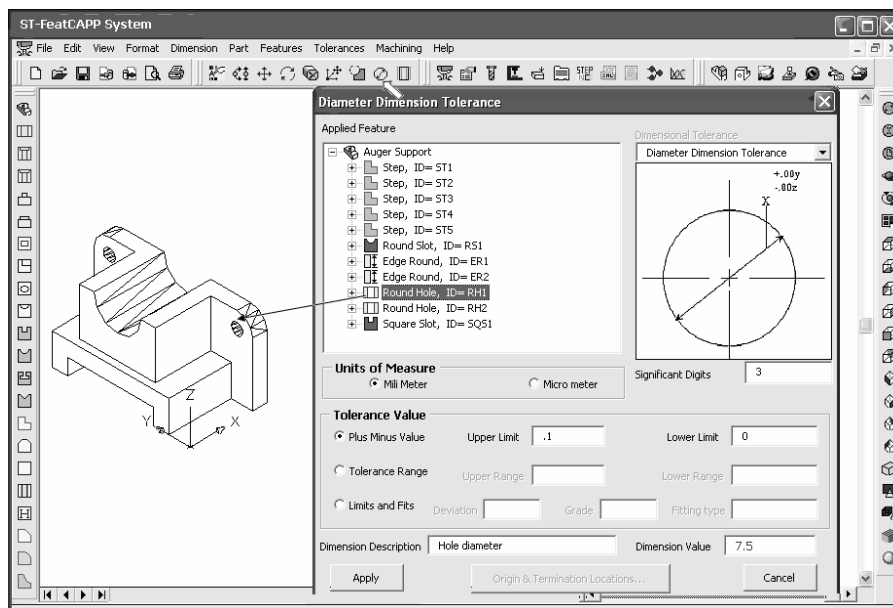


Figure 6.21 Dimensional tolerances attachment process window

The attachment of geometrical tolerance involves selecting the geometrical tolerance type, defining the tolerance values and attributes, defining datum, and selecting the feature to which this tolerance is being applied. Figure 6.22 shows the attachment of the cylindricity tolerance to the round slot feature (RS1).

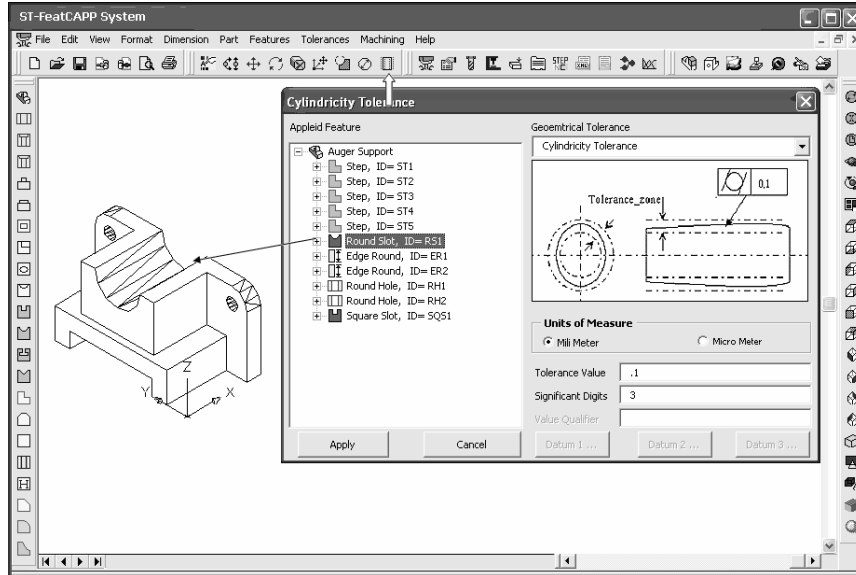


Figure 6.22 Geometrical tolerances attachment process window

Figure 6.23 shows the assignment of surface finish property to the step feature (ST3). The assignment involves defining the surface finish property value and selecting the feature to which it will be applied

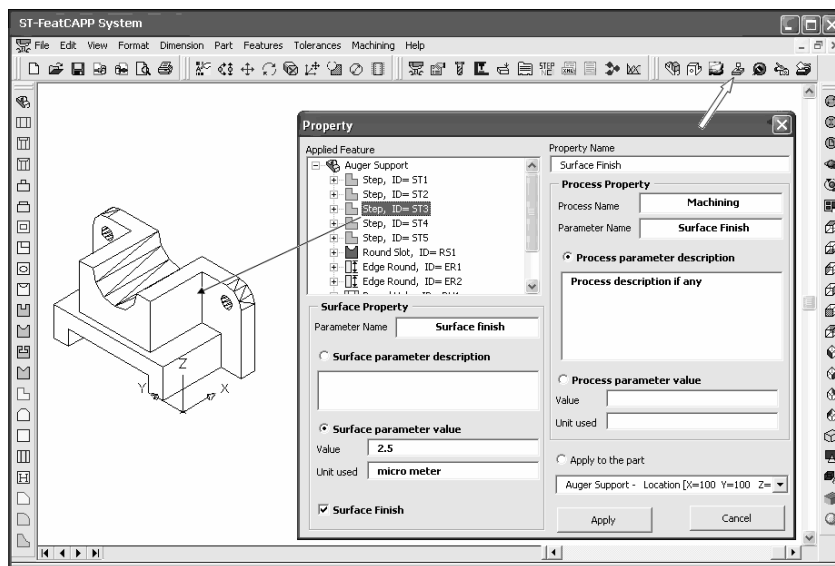


Figure 6.23 Process and surface properties attachment process window

Figure 6.24 shows the assignment of part material, alternate material, stock size and material hardness.

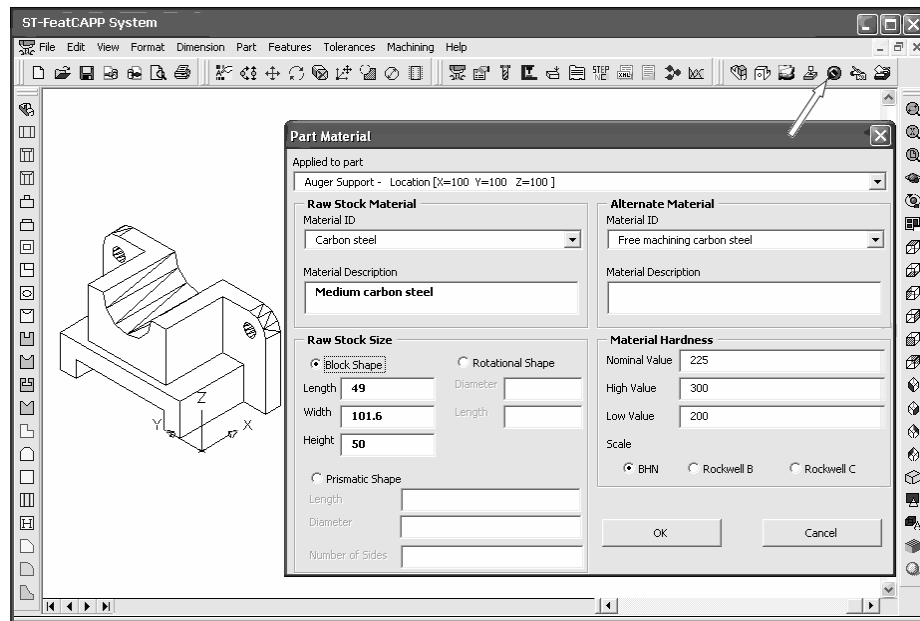


Figure 6.24 Material assignment window

The administrative data needed to track the part during or after the manufacturing can be entered from the customer order window, Figure 6.25 shows an example of this window. Several other administrative data windows can be displayed and filled with the required data.

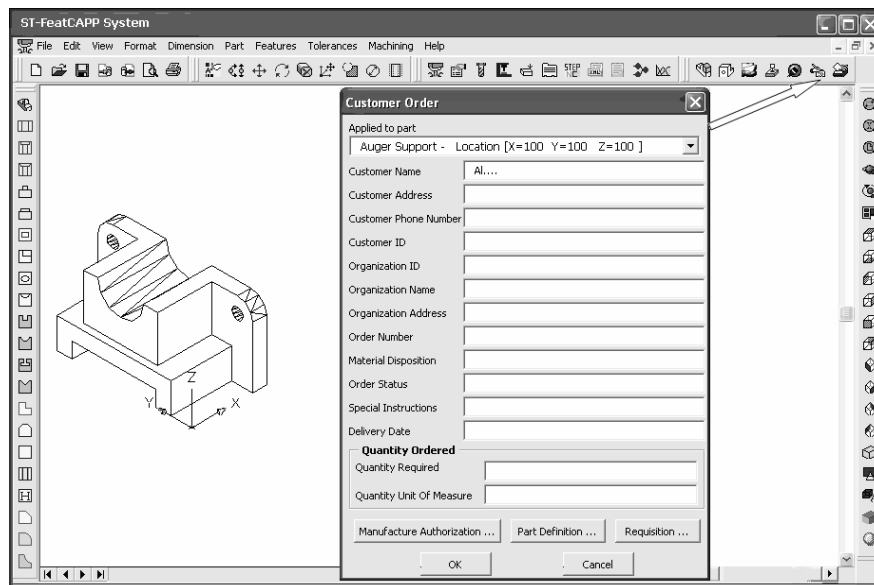


Figure 6.25 Administrative data assignment window

6.6 Process Planning Example with ST-FeatCAPP

To demonstrate the application of the developed process planning system, an example part is presented in this section to illustrate the process planning tasks of ST-FeatCAPP system. The following paragraphs and figures show the different tasks of process planning of a clamping plate example part.

ST-FeatCAPP is a STEP feature-based, fully generative and intelligent process planning system. It reads part data in terms of high-level machining features and their technical attributes based on STEP-224. The output of the system is a high-level digital process plan in XML format based on STEP-NC.

The part data can be fed to the system by two methods. In the first method, Figure 6.26, a feature-based model designed and saved previously by STE-FM modeler is loaded using open existing part command. The data file structure of this model is a STEP-FM specific data format.

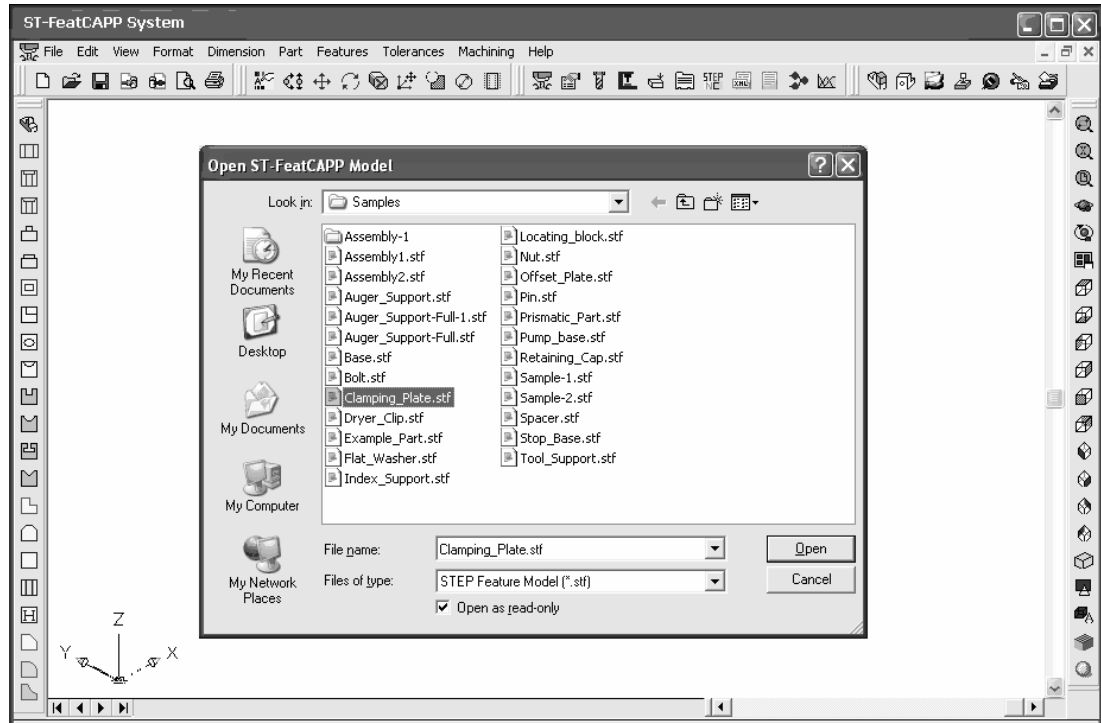


Figure 6.26 Open existing part window

In the second method, Figure 6.27, the part data is imported from STEP-224 XML file. This file is generated by STEP-FM modeler and structured based on STEP-28.

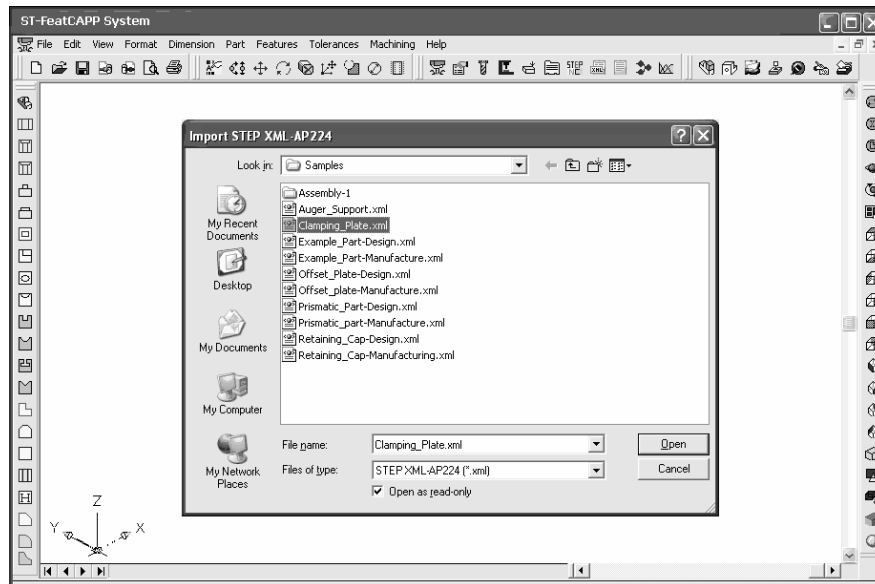


Figure 6.27 Import STEP AP224 XML data file window

Once the part is loaded or imported to the system, the solid model will be generated and ST-FeatCAPP and AutoCAD command can be performed on the model (Figure 6.28).

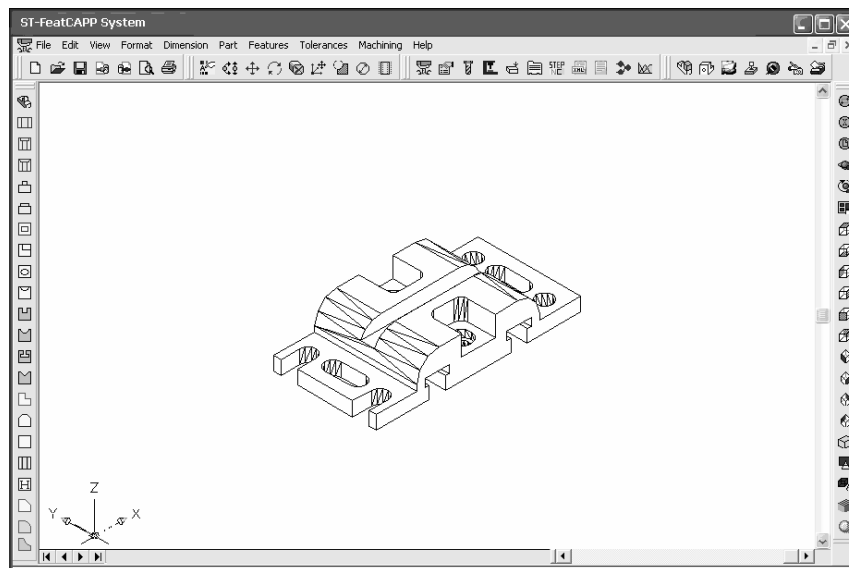


Figure 6.28 Example part for process planning

The part features data and their technical attributes can be viewed using the feature properties command. This is to verify that all part data required for process planning are loaded (Figure 6.29).

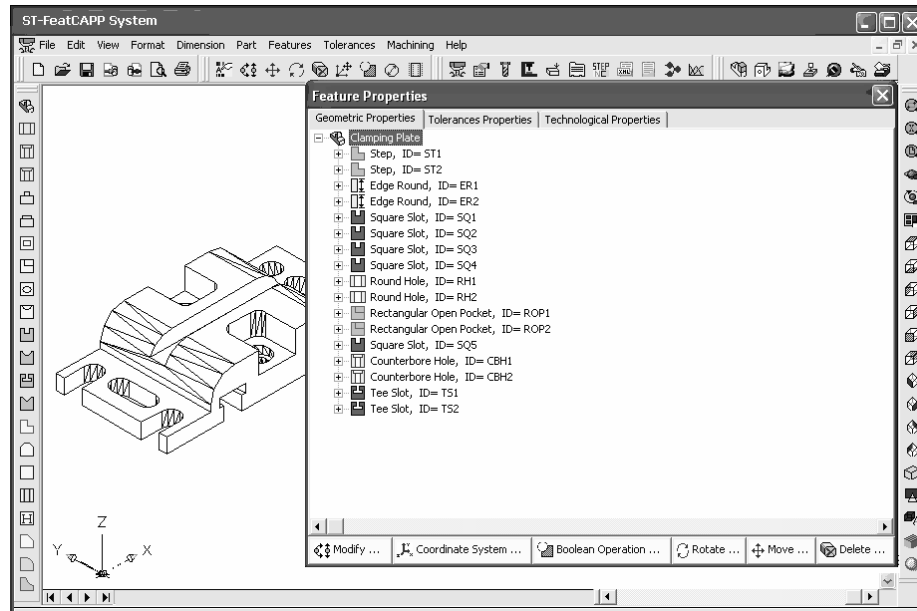


Figure 6.29 Example part features data and attributes window

Figure 6.30 shows the machining operations required to machine each feature. Machining operations can be displayed at any time to check their parameters.

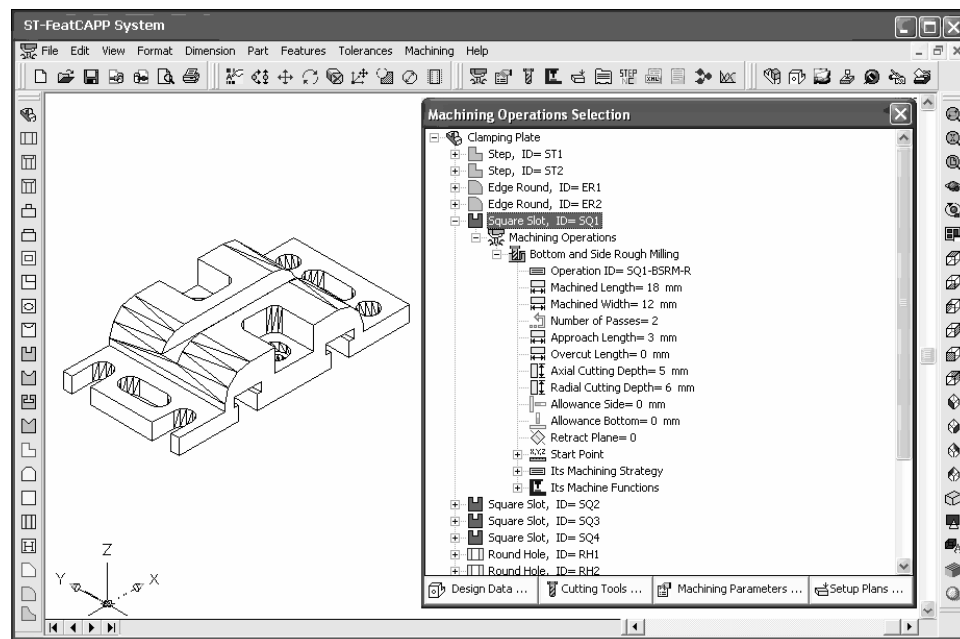


Figure 6.30 Example part machining operations window

Figure 6.31 shows the machining parameters selected for each machining operation. Other machining parameters are calculated and displayed in the same window.

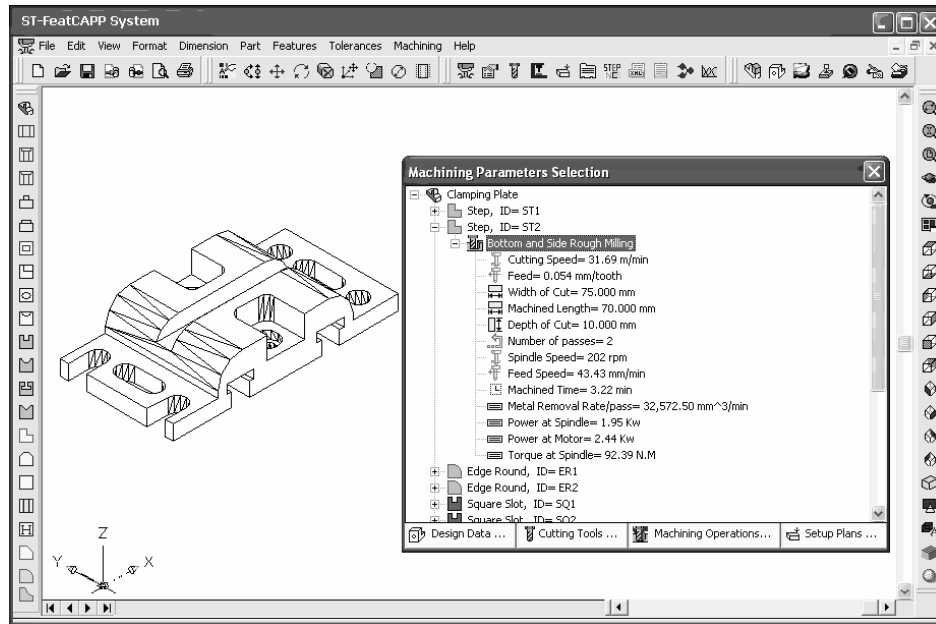


Figure 6.31 Example part machining parameters window

Figure 6.32 shows the cutting tools for each machining operation. Tools dimension and geometry can be checked and verified at this window.

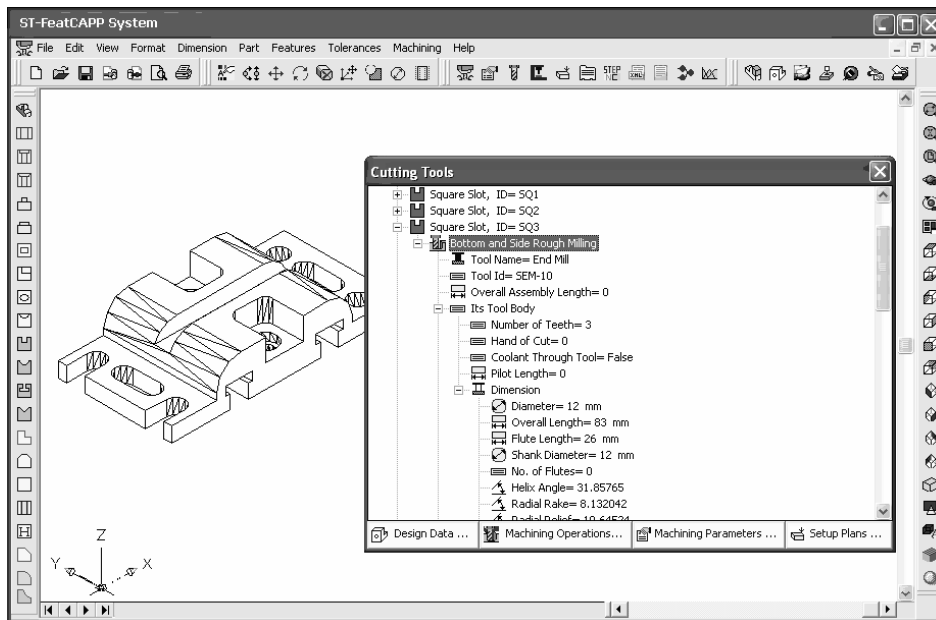


Figure 6.32 Example part cutting tools window

The setup plans needed to machine the part can be displayed using setup plans window (Figure 6.33). This window contains setup plans with their associated machining features and operations.

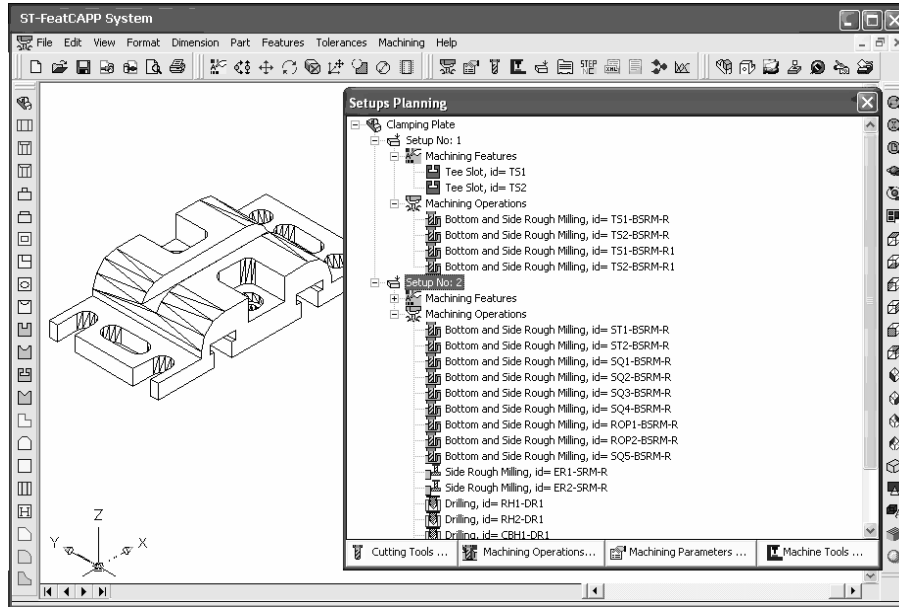


Figure 6.33 Example part setup plans window

Figure 6.34 shows the process plan for the selected manufactured part. Machining features, machining operations, cutting parameters, calculations of time and power, and cutting tools needed are all displayed in this process plan.

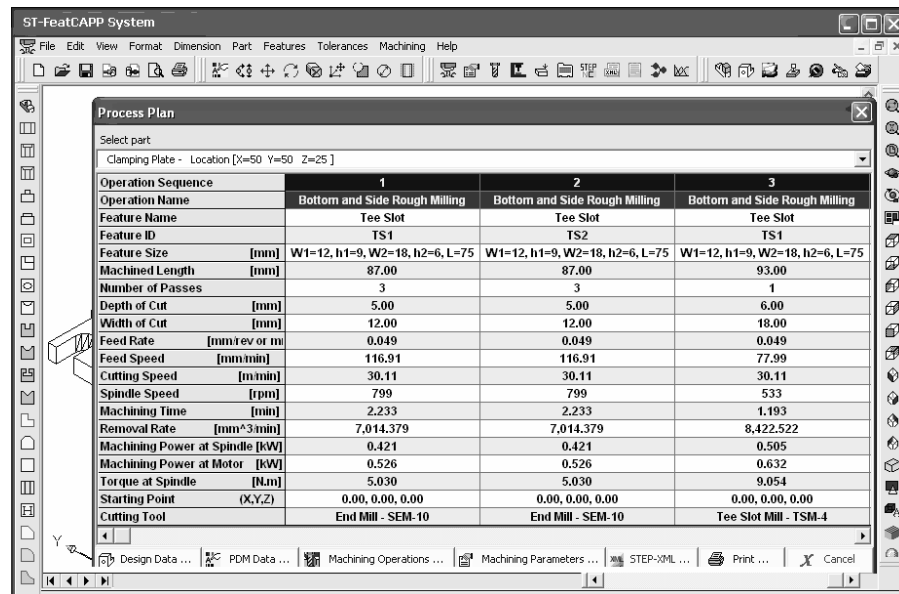


Figure 6.34 Example part process plan window

ST-FeatCAPP is an intelligent CAPP system based mainly on neural networks and fuzzy logic approaches. Figure 6.36 shows the architectural and training properties of the implemented neural networks, It is possible to train these networks by selecting the neural network task and pressing the learning button. A neural network training window will appear as shown in Figure 6.37. Adding new training patterns to the selected network task is done by pressing the training pattern button. Starting the training session is done by pressing the train button. It should be noted that the training process may take several minutes to reach to the target error.

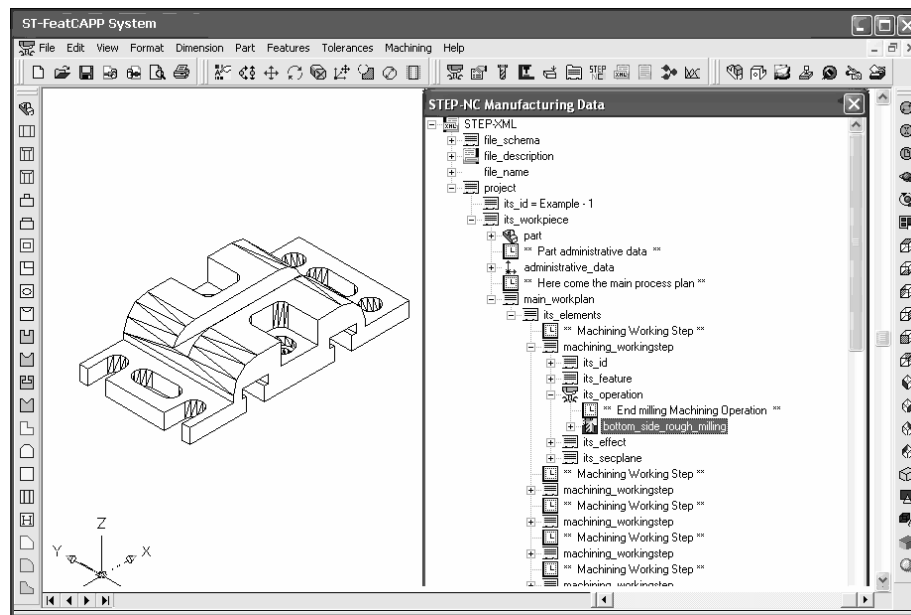


Figure 6.35 Example part STEP-NC data window

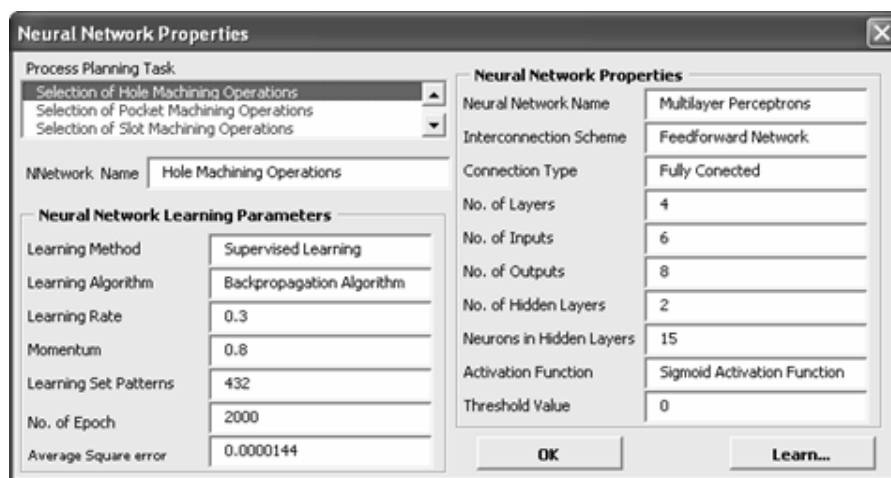


Figure 6.36 Neural networks properties window

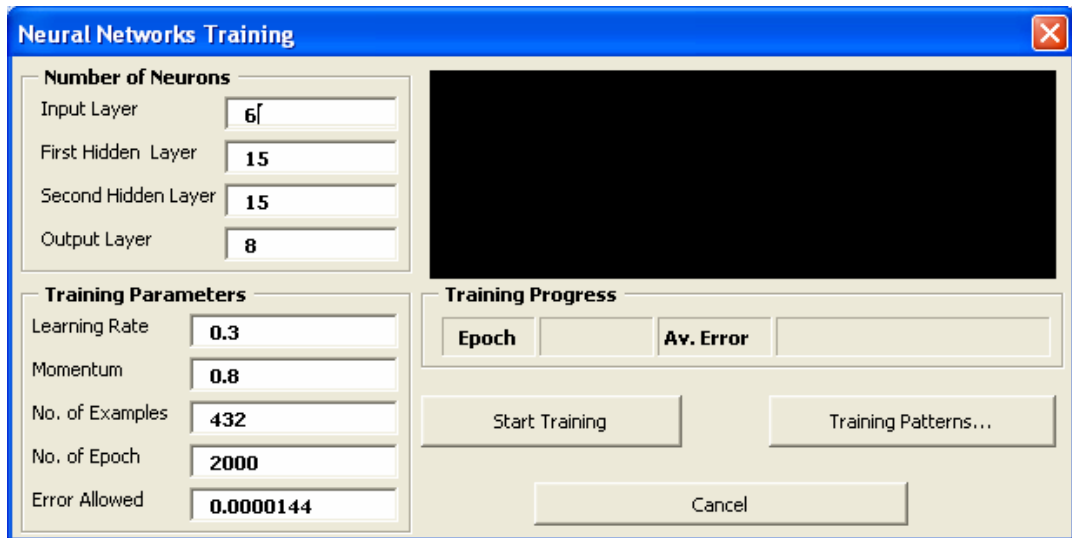


Figure 6.37 Neural networks training window

Figure 6.38 presents the fuzzy knowledge base utilized by the system. It consists of a number of fuzzy rules based on work material, machining operation and tool material combination. These fuzzy rules can be modified by selecting a specified rule and pressing the modify rule button. A fuzzy rule update window will appear as shown in Figure 6.39. The selected rule is then modified and updated.

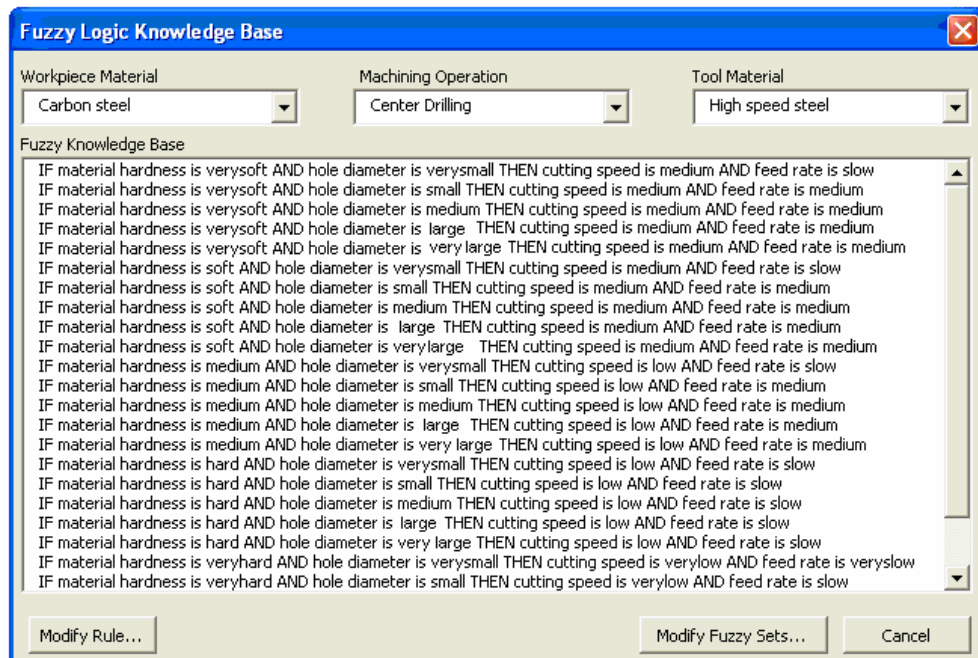


Figure 6.38 Fuzzy logic knowledge base window

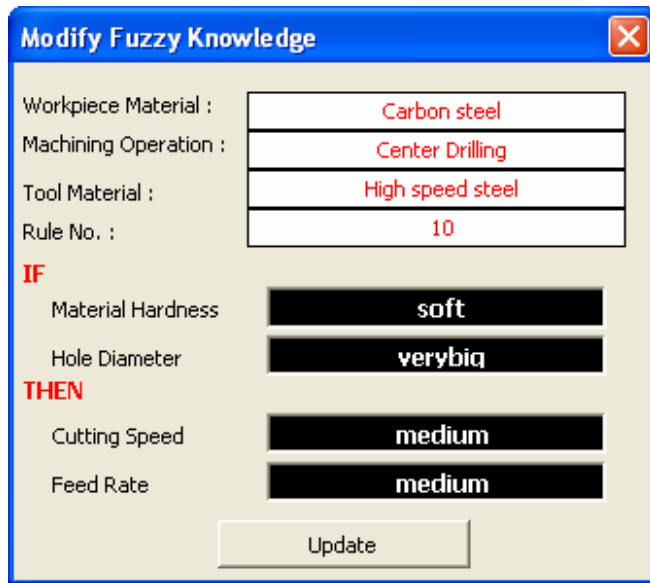


Figure 6.39 Fuzzy knowledge update window

It is also possible to control the limits of the fuzzy sets used by the fuzzy variables in these rules. The "modify fuzzy set" button is used to show the window in Figure 6.40. The fuzzy set modification is accomplished by selecting the required fuzzy variable and then assigning new values for minimum, mid and maximum values for each fuzzy set.

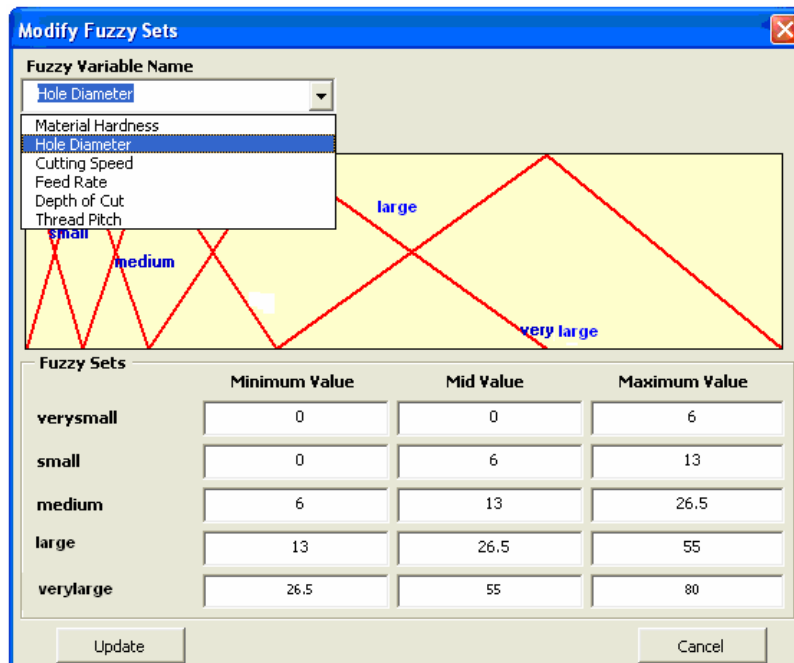


Figure 6.40 Fuzzy sets modification window

Default values for ST-FeatCAPP machining operations can be set using machining operations setting window shown in Figure 6.41.

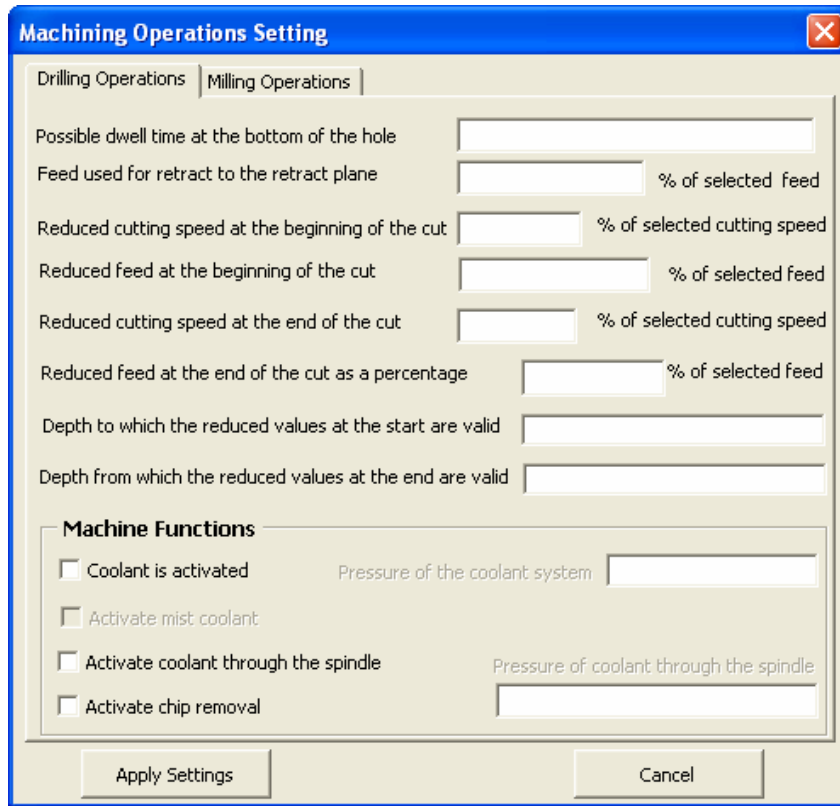


Figure 6.41 Machining operations settings window

Figure 6.42 shows the cutting tools library utilized by the system. From this tools library, the system can be updated with a new cutting tools data and browse the existing cutting tools.

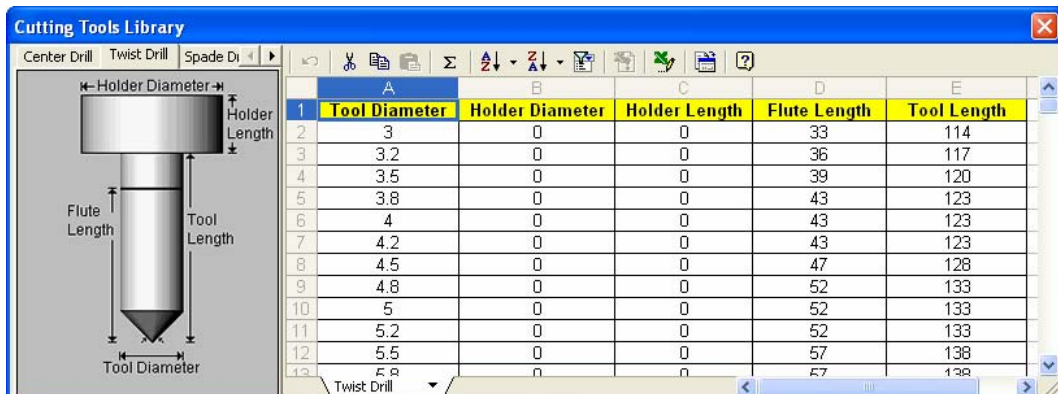


Figure 6.42 Cutting tools library window

Tool materials and their hardness values can be set as default values for cutting tools from the tool setting window shown in Figure 6.43. Two types of tool materials are supported by ST-FeatCAPP system; high speed steel and carbide.



Figure 6.43 Cutting tools materials window

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This research work is motivated by industrial requirements of concurrent engineering, standard product data models, and integrated manufacturing environment, which are further reflected in process planning as integrated and intelligent CAPP systems. This research work focuses on feature-based modeling, intelligent process planning, and generation of digital process plans. The conclusions of the work can be elaborated in the following details.

- In this research, an integrated CAD/CAPP system that integrates design and process planning has been developed and implemented. In the design stage, a STEP-based feature modeler, STEP-FM, has been developed for modeling mechanical parts. In process planning stage, a hybrid intelligent process planning system, ST-FeatCAPP, has been developed. In both systems, STEP has been adopted as the product model to facilitate the integration and implementation processes.
- The STEP-FM is developed as a design by feature tool to integrate design and manufacturing tasks. STEP-FM uses high-level 3D features as the basic design entities in the design process. The modeler relies on three main steps; (1) selection of the part base shape and overall size, (2) selection of the features to be added to or subtracted from the part designed, and (3) providing information needed to define feature size, position orientation and other attributes such as surface finish, tolerances, etc. The approach of design

by feature allows the designer to concentrate more on design-concept representations than on drafting operations. This is considered as an advantage of using features in design process. Also, designers can consider manufacturing properties earlier in the part design phase. The part data file, which is generated by STEP-FM and saved in STEP-AP224 XML format, can be passed directly to the downstream CAM activities without using feature recognition. The feature modeler can be used to design several types of mechanical parts. In addition, it facilitates the integration process of CAD/CAPP systems.

- The ST-FeatCAPP system is a hybrid intelligent process planning system using STEP-based features. The system maps STEP AP224 XML data file, without using a complex feature recognition process, and produces the corresponding machining operations to generate the process plan and corresponding STEP-NC in XML format. ST-FeatCAPP carries out several stages of process planning utilizing a hybrid approach of most recent techniques of artificial intelligence as the inference engine. Artificial neural networks have been used to select machining operations, cutting tools, and machine tools. Several neural networks have been designed, trained and implemented in ST-FeatCAPP system to carry out the above mentioned tasks of process planning. A number of fuzzy logic models have been implemented to select machining parameters for several machining operations, cutting tool materials, and workpiece materials combinations. Setup planning is carried out based on a number of machining rules utilized by a simple setup planning algorithm. The use of hybrid approach of neural networks and fuzzy logic has enabled the development of flexible CAPP system that can be trained to handle new knowledge. The output of ST-FeatCAPP system is a STEP-NC process plan which can be used to control the next generation of intelligent machine tool controllers.
- An object oriented approach has been used in the definition and implementation of the developed systems since it represents a logical means

for representing real-world objects like machined parts. Compared with traditional approaches to design and implementation of data modeling and software systems, this approach offers advantages of increased flexibility, incremental system development and reusability. Unified Modeling Language, UML, is used for specifying, constructing, and documenting the developed systems. Several UML class models have been constructed for manufactured part, machining features, machining operations to specify the properties used and the operations to be performed.

- The output of the developed process planning system, ST-FeatCAPP, is a digital type process plan according to STEP-NC data model. This process plan contains a pair of ISO standards, ISO 14649 and ISO 10303 AP238, which together define machining and tooling requirements for drilling and milling operations, and integrate these data models into the existing STEP framework. The main goal of the generated process plan is to tie together design, process planning, and machining into a seamless flow of data. The digital process plan is based on the concept of machining features rather than primitive point-to-point tool motion. In downstream direction, design changes such as feature locations or tolerances can be conveyed through automated process planning system and onto machine tools, eliminating tedious hand editing of different file formats whenever changes are made. In the upstream direction, changes to machining programs made on the shop floor can be made available automatically to design and process planning system, so that lessons learned in production tests can be relayed more efficiently to designers and process planners. Perhaps more importantly, the availability of the rich information afforded by STEP-NC process plan enables true intelligent control, in which machine tools have access to material information, tolerances, and the logical flow of working steps.
- Microsoft Visual BASIC, VBA, dynamic library link, and activex technology have been used as programming tools for development and implementation of the developed systems in this research work. System integration becomes

easier to implement because of AutoCAD objects through an activex interface and programming those objects using the visual BASIC for applications (VBA) programming environment. AutoCAD activex interface provides a mechanism to manipulate AutoCAD programmatically from within or outside AutoCAD. The integration of the developed systems is done by adding the feature modeler, STEP-FM, and process planning, ST-FeatCAPP, interfaces and commands to AutoCAD. By this way, AutoCAD became capable of providing geometrical modeling, feature modeling, and performing intelligent process planning tasks.

7.2 Research Contributions

The main objectives of this research work is to develop an integrated, STEP-based, intelligent process planning system that helps designers and process planners to improve their design and planning in the early stages of the product development process. These objectives are realized through the following contributions.

- *Implementation of a high-level product data model using STEP standard.*
This research implements a STEP-based product data modeling approach that takes into account all the aspects of a product data. The model supports process planning of mechanical parts in terms of manufacturing features. It includes almost all the information required to develop and implement a CAPP system. The product model also adopts the object-oriented modeling methodology, so that the CAPP system can be easily developed, maintained and extended. The use of EXPRESS as a product data modeling language enhances the CAPP system to be integrated with other systems in the CIM environment. Perhaps, the most recent contribution is the generation of STEP data in XML format to facilitate the linking of CAPP system with CAx systems.

- *New generation feature-based design system.* This research work presents a new type feature based design system for designing mechanical parts using standard feature based on STEP AP224 standard. The system generates a STEP XML data files contains explicit high-level product data in terms of feature attributes, tolerances, material specifications, etc. This file can be used directly with process planning systems without using a complex feature recognition process.
- *Integrated feature-based CAPP system.* The feature-based CAPP system described in this thesis demonstrates a feasible and attractive approach for implementation of a process planning system that can be integrated with design, manufacturing, product data management, and several other related modules within a computer integrated manufacturing system. The framework presented in this CAPP system is believed to contribute towards removing the main barrier to automated process planning, i.e. difficulty in recognizing machining features and technological information.
- *Intelligent CAPP system.* The work done for developing an intelligent CAPP system in this research, has significantly contributed to the applicability of advanced artificial intelligent techniques (neural networks and fuzzy logic) in CAPP systems. The use of these techniques has enabled the development of a very flexible CAPP methodology that can be easily trained to handle new knowledge. In addition, these techniques will provide the basis for extending these techniques to construct a complete process planning system.
- *STEP feature technology.* This research work is considered a pioneering work to implement STEP feature technology in integrating an existing CAD system with computer aided process planning system. It has enabled an effective concurrent engineering tool that can bridge the gap between design and manufacturing.

- *Generation of STEP-NC process plan.* The most recent contribution of this research work is the generation of STEP-NC process plan. STEP-NC defines a new interface for a more effective, bi-directional information exchange between CAD/CAM systems and NC controllers. It is a feature-based, object-oriented structure, fully compatible with the widely disseminated STEP standard (10303). With STEP-NC, all CAD, CAM and NC data can be stored in a single database, to which each CAx system or NC controller can have access for information retrieved, alteration and appending. This is a consistent STEP-NC data set, containing all the relevant information to realize an intelligent and productive production.

7.3 Research Limitations

The main emphasis in this thesis has been to develop a feature-based intelligent process planning system for prismatic parts. However, due to a large number of practical limitations such as software libraries, product data translators, and so forth, the current implementation has several restrictions on the type of parts handled and the STEP-NC process plan generated by the system. Some of the main restrictions are described below.

- Features supported by the developed feature modeler (STEP-FM) are restricted to a set of 3-axis milling and drilling operations features.
- The machining features considered in process planning are limited to hole features, slot features, pocket features, transition features, and step features.
- In ST-FeatCAPP system, the initial raw stock of the part to be machined is restricted to a block base shape with exact overall size.
- All operations of a feature are finished in one setup.
- In STEP-NC process plan, tool path planning is not included and considered as optional information which can be added later.
- The architecture of the neural networks implemented in this research are based on four-layered networks with fixed two hidden layers and variable

hidden neurons. The backpropagation algorithm is used in the training process.

- The fuzzy logic model implemented in this research is limited to two input variables and two output variables. The triangular-shaped membership function and center of area defuzzification method are used in the model.
- The developed software is totally running within AutoCAD environment.

7.4 Recommendations for future research

In order to build an integrated CAD/CAPP system for real-life parts, several extensions will be needed to this research. Of course, there is always room for such extensions, and in this work only limited solutions are provided for feature-based design and process planning problems. Below are some of the recommendations for future extensions.

- STEP-FM is a first step in the direction of a standard feature-based design system and, as in any initial system, must be improved to include more design steps.
- Features considered in this research are restricted to a set of 3-axis milling and drilling machining features, based on STEP-AP224 developed for mechanical product definition for computerized process planning using for features. Future work, including turning and profile milling machining features is highly recommended to extend this research.
- Developing a stand-alone feature-based system that is CAD system independent is recommended to be the next step. The Activex interface functions used in this research are AutoCAD functions. When other CAD systems are used as the working design environment, the interface commands may need to be changed, since different CAD developers have their own programming interface functions. In order to avoid this problem, instead of

using CAD interface functions, a stand-alone feature modeler is required so that the feature-based systems become independent of a particular CAD system.

- This research takes major steps towards the application of advanced artificial intelligence in computer aided process planning by developing a hybrid approach consisting of artificial neural networks and fuzzy logic. However, this approach can be extended to carry out other tasks of process planning including setup planning, fixture planning, and manufacturing cost estimation. In addition, the use of optimization algorithms for learning neural networks and fuzzy logic can enhance the ability of CAPP system to handle complex parts.
- The proposed setup planning algorithm in this research work utilizes a simple setup planning principles. Only tool access direction and feature precedence are considered. Tolerance relationships are critical for setup planning in precision manufacturing. Comprehensive analysis for both dimensional and geometrical tolerances is recommended for the future work. Hence, comprehensive exploration and computerization of setup planning rules and principles still deserve a lot of work.
- In this thesis, fixture planning task is not considered. In order to have a complete CAPP system, fixture planning is needed. The fixture planning task should be feature-based and fully integrated with the system developed in this thesis (ST-FeatCAPP).
- STEP-NC process plan is currently being validated in pilot projects both in the U.S. (titles as "Super Model") and in Europe (titled as "STEP-NC"). To date validation has focused on feature-based machining for a limited number of features. This research has focused on producing STEP-NC process plan for a limited number of machining features without tool path planning. In STEP-NC, tool path planning is optional information which can be added to

the process plan at later stages. Perhaps, the most important future work on STEP-NC will include more machining features and generating path planning to enable true intelligent control of CNC machines.

It is expected that the recommended future extensions will enhance the usefulness of this research, and will result in development of a fully integrated and intelligent CAPP system.

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APPENDIX A

STEP-FM/ST-FeatCAPP SAMPLE RESULTS

A1. Clamping Plate Example

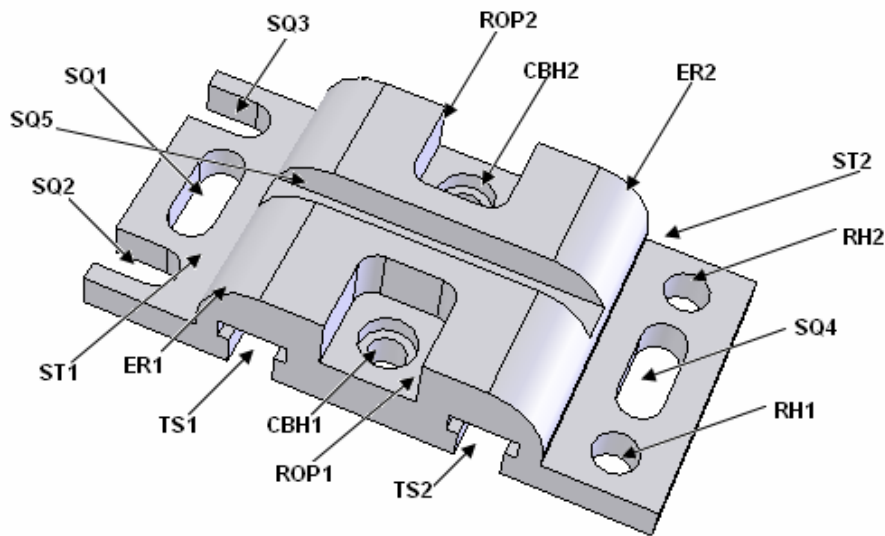


Figure A.1 Clamping plate Model

Table A.1 Machining Features List for Clamping Plate

Feature name	Feature id	Feature size	Location	Orientation
Block base shape, L=150 , W=75 , H=30				
Step	ST1	W=75, h=20, L=30	X=65,Y=87.5,Z=45	XY Top
Step	ST2	W=75, h=20, L=30	X=185,Y=87.5,Z=45	XY Top
Edge round	ER1	R=16, L=75	X=80,Y=87.5,Z=55	XY Top
Edge round	ER2	R=16, L=75	X=170,Y=87.5,Z=55	XY Top
Square slot	SQ1	W=12, L=30, h=10	X=65,Y=87.5,Z=35	XY Top
Square slot	SQ2	W=12, L=20, h=10	X=60,Y=61.25,Z=35	XY Top
Square slot	SQ3	W=12, L=20, h=10	X=60,Y=113.75,Z=35	XY Top
Square slot	SQ4	W=12, L=30, h=10	X=185,Y=87.5,Z=35	XY Top
Round hole	RH1	D=12, L=10	X=185,Y=61.25,Z=35	XY Top
Round hole	RH2	D=12, L=10	X=185,Y=113.75,Z=35	XY Top
Rectangular open pocket	ROP1	W=25, L=25, h=25	X=125,Y=62.5,Z=55	XY Top

Table A.1 (Continues) Machining Features List for Clamping Plate

Feature name	Feature id	Feature size	Location	Orientation
Rect. open pocket	ROP2	W=25, L=25, h=25	X=125,Y=112.5,Z=55	XY Top
Square slot	SQ5	W=10, L=90, h=10	X=125,Y=87.5,Z=55	XY Top
Counterbore hole	CBH1	D1=10, L1=15, D2=15, L2=5	X=125,Y=62.5,Z=40	XY Top
Counterbore hole	CBH2	D1=10, L1=15, D2=15, L2=5	X=125,Y=112.5,Z=40	XY Top
Tee slot	TS1	W1=12, h1=9, W2=18, h2=6, L=75	X=95,Y=87.5,Z=25	XY Bottom
Tee slot	TS2	W1=12, h1=9, W2=18, h2=6, L=75	X=155,Y=87.5,Z=25	XY Bottom

Table A.2 Machining Operations for Clamping Plate

Operation Name	Operation Id	Feature Id	Length	Width	Depth	Pass
-	-	-	mm	mm	mm	-
Bottom and Side Rough Milling	TS1-BSRM-R	TS1	87	12	5	3
Bottom and Side Rough Milling	TS2-BSRM-R	TS2	87	12	5	3
Bottom and Side Rough Milling	TS1-BSRM-R1	TS1	93	18	6	1
Bottom and Side Rough Milling	TS2-BSRM-R1	TS2	93	18	6	1
Bottom and Side Rough Milling	ST1-BSRM-R	ST1	70	75	10	2
Bottom and Side Rough Milling	ST2-BSRM-R	ST2	70	75	10	2
Bottom and Side Rough Milling	SQ1-BSRM-R	SQ1	20	10	4.5	2
Bottom and Side Rough Milling	SQ2-BSRM-R	SQ2	20	12	5	2
Bottom and Side Rough Milling	SQ3-BSRM-R	SQ3	20	12	5	2
Bottom and Side Rough Milling	SQ4-BSRM-R	SQ4	20	10	4.5	2
Bottom and Side Rough Milling	ROP1-BSRM-R	ROP1	25	8.33	5	5
Bottom and Side Rough Milling	ROP2-BSRM-R	ROP2	25	8.33	5	5
Bottom and Side Rough Milling	SQ5-BSRM-R	SQ5	98	8	3	3
Side Rough Milling	ER1-SRM-R	ER1	95.08	12.57	4.69	1
Side Rough Milling	ER2-SRM-R	ER2	95.08	12.57	4.69	1
Center Drilling	RH1-CDR	RH1	3	4	N/A	1
Center Drilling	RH2-CDR	RH2	3	4	N/A	1
Drilling	RH1-DR1	RH1	16	11	N/A	1
Drilling	RH2-DR1	RH2	16	11	N/A	1
Drilling	CBH1-DR1	CBH1	21	10	N/A	1
Drilling	CBH2-DR1	CBH2	21	10	N/A	1
Counterboring	CBH1-CB	CBH1	8	15	N/A	1
Counterboring	CBH2-CB	CBH2	8	15	N/A	1
Reaming	RH1-R	RH1	16	12	0.5	1
Reaming	RH2-R	RH2	16	12	0.5	1
Bottom and Side Finish Milling	SQ1-BSFM-F	SQ1	18	2	1	1
Bottom and Side Finish Milling	SQ4-BSFM-F	SQ4	18	2	1	1
Bottom and Side Finish Milling	SQ5-BSFM-F	SQ5	100	2	1	1

Table A.3 Machining Parameters for Clamping Plate

Operation Id	Cutting Speed	Feed Rate	Feed Speed	RPM	Machined Time	Removal Rate	Machining Power
-	m/min	mm/r	mm/min	rpm	min	mm ³ /min	Kw
TS1-BSRM-R	19.56	0.048	75.15	519	3.47	4,509.23	0.27
TS2-BSRM-R	19.56	0.048	75.15	519	3.47	4,509.23	0.27
TS1-BSRM-R1	19.38	0.047	48.02	343	1.94	5,186.16	0.31
TS2-BSRM-R1	19.38	0.047	48.02	343	1.94	5,186.16	0.31
ST1-BSRM-R	20.36	0.054	27.95	130	5.01	20,962.50	1.26
ST2-BSRM-R	20.36	0.054	27.95	130	5.01	20,962.50	1.26
SQ1-BSRM-R	19.76	0.05	93.76	629	0.43	4,218.98	0.25
SQ2-BSRM-R	19.56	0.048	75.15	519	0.53	4,509.23	0.27
SQ3-BSRM-R	19.56	0.048	75.15	519	0.53	4,509.23	0.27
SQ4-BSRM-R	19.76	0.05	93.76	629	0.43	4,218.98	0.25
ROP1-BSRM-R	19.56	0.048	90.21	623	4.16	3,758.90	0.23
ROP2-BSRM-R	19.56	0.048	90.21	623	4.16	3,758.90	0.23
SQ5-BSRM-R	20.65	0.056	137.31	822	2.14	3,295.47	0.2
ER1-SRM-R	20.05	0.353	143.94	51	0.66	8,476.60	0.51
ER2-SRM-R	20.05	0.353	143.94	51	0.66	8,476.60	0.51
RH1-CDR	20.02	0.291	464.21	593	0.01	5,833.46	0.35
RH2-CDR	20.02	0.291	464.21	593	0.01	5,833.46	0.35
RH1-DR1	19.87	0.297	170.72	575	0.09	16,224.48	0.97
RH2-DR1	19.87	0.297	170.72	575	0.09	16,224.48	0.97
CBH1-DR1	20.36	0.281	182.12	648	0.12	14,303.78	0.86
CBH2-DR1	20.36	0.281	182.12	648	0.12	14,303.78	0.86
CBH1-CB	19.53	0.345	142.91	414	0.06	14,029.84	0.84
CBH2-CB	19.53	0.345	142.91	414	0.06	14,029.84	0.84
RH1-R	19.52	0.316	163.46	518	0.1	2,952.73	0.18
RH2-R	19.52	0.316	163.46	518	0.1	2,952.73	0.18
SQ1-BSFM-F	19.56	0.048	75.15	519	0.24	150.31	0.01
SQ4-BSFM-F	19.56	0.048	75.15	519	0.24	150.31	0.01
SQ5-BSFM-F	19.56	0.048	90.21	623	1.11	180.43	0.01

Table A.4 Cutting Tools for Clamping Plate

Operation Id	Tool Name	Tool Id	Tool Diameter	Flute Length	Tool Material
-	-	-	mm	mm	-
TS1-BSRM-R	End Mill	SEM-10	12	83	HSS
TS2-BSRM-R	End Mill	SEM-10	12	83	HSS
TS1-BSRM-R1	Tee Slot Mill	TSM-4	18	70	HSS
TS2-BSRM-R1	Tee Slot Mill	TSM-4	18	70	HSS
ST1-BSRM-R	Face Mill	FM-5	50	0	HSS
ST2-BSRM-R	Face Mill	FM-5	50	0	HSS
SQ1-BSRM-R	End Mill	SEM-10	10	72	HSS
SQ2-BSRM-R	End Mill	SEM-10	12	83	HSS
SQ3-BSRM-R	End Mill	SEM-10	12	83	HSS
SQ4-BSRM-R	End Mill	SEM-10	10	72	HSS
ROP1-BSRM-R	End Mill	SEM-9	10	72	HSS
ROP2-BSRM-R	End Mill	SEM-9	10	72	HSS
SQ5-BSRM-R	End Mill	SEM-9	8	69	HSS
ER1-SRM-R	Rounding Corner Mill	RCM-16	125	0	HSS
ER2-SRM-R	Rounding Corner Mill	RCM-16	125	0	HSS
RH1-CDR	Center Drill	CD-6	4	0	HSS
RH2-CDR	Center Drill	CD-6	4	0	HSS
RH1-DR1	Twist Drill	TWD-33	11	175	HSS
RH2-DR1	Twist Drill	TWD-33	11	175	HSS
CBH1-DR1	Twist Drill	TWD-29	10	168	HSS
CBH2-DR1	Twist Drill	TWD-29	10	168	HSS
CBH1-CB	Counterbore	CB-49	15	0	HSS
CBH2-CB	Counterbore	CB-49	15	0	HSS
RH1-R	Reamer	RM-37	12	0	HSS
RH2-R	Reamer	RM-37	12	0	HSS
SQ1-BSFM-F	End Mill	SEM-10	12	83	HSS
SQ4-BSFM-F	End Mill	SEM-10	12	83	HSS
SQ5-BSFM-F	End Mill	SEM-9	10	72	HSS

A2. Retaining Cap Example

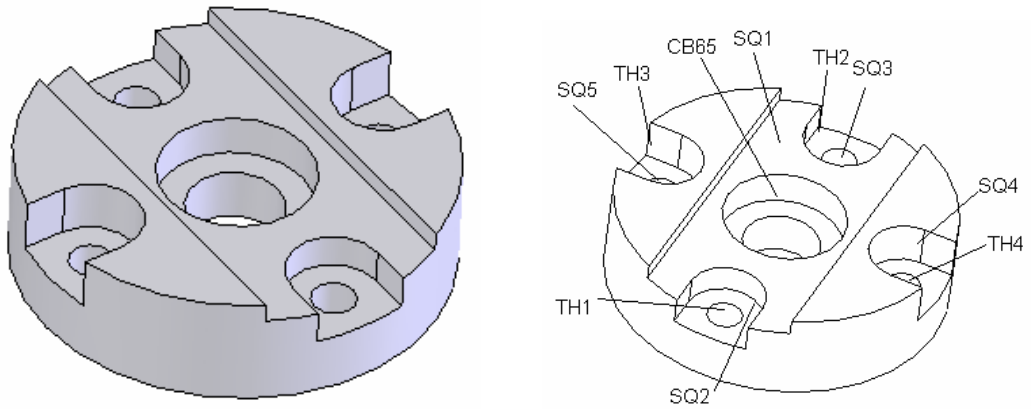


Figure A.2 Retaining Cap Model

Table A.5 Machining Features List for Retaining Cap

Feature name	Feature id	Feature size	Location	Orientation
Cylindrical base shape, L= 30, D=110				
Square slot	SQ1	L=110, w=50, h=5	x=50, y=50, z=55	XY-top
Counterbore hole	CB65	D=40, L1=11, d=25, L2=14	x=50, y=50, z=50	XY-top
Square slot	SQ2	L=25, w=25, h=14	x=7.5, y=50, z=55	XY-top
Square slot	SQ3	L=25, w=25, h=14	x=92, y=50, z=55	XY-top
Square slot	SQ4	L=25, w=25, h=14	x=50, y=92, z=55	XY-top
Square slot	SQ5	L=25, w=25, h=14	x=50, y=7.5, z=55	XY-top
Round hole	TH1	D=11.5, L=16	x=7.5, y=50, z=41	XY-top
Round hole	TH2	D=11.5, L=16	x=92, y=50, z=41	XY-top
Round hole	TH3	D=11.5, L=16	x=50, y=7.5, z=41	XY-top
Round hole	TH4	D=11.5, L=16	x=50, y=92, z=41	XY-top

Table A.6 Machining Operations for Retaining Cap

Operation Name	Operation Id	Feature Id	Length	Width	Depth	Passes
-	-	-	mm	mm	mm	-
Bottom and Side Rough Milling	SQ1-BSRM-R	SQ1	155	45	4	1
Bottom and Side Rough Milling	SQ2-BSRM-R	SQ2	25	22	6.5	2
Bottom and Side Rough Milling	SQ3-BSRM-R	SQ3	25	22	6.5	2
Bottom and Side Rough Milling	SQ4-BSRM-R	SQ4	25	22	6.5	2
Bottom and Side Rough Milling	SQ5-BSRM-R	SQ5	25	22	6.5	2
Center Drilling	CB65-CDR	CB65	3	8.2	N/A	1
Center Drilling	TH1-CDR	TH1	3	3.8	N/A	1
Center Drilling	TH2-CDR	TH2	3	3.8	N/A	1
Center Drilling	TH3-CDR	TH3	3	3.8	N/A	1
Center Drilling	TH4-CDR	TH4	3	3.8	N/A	1
Drilling	CB65-DR1	CB65	31	12.5	N/A	1
Drilling	TH1-DR1	TH1	22	10.5	N/A	1
Drilling	TH2-DR1	TH2	22	10.5	N/A	1
Drilling	TH3-DR1	TH3	22	10.5	N/A	1
Drilling	TH4-DR1	TH4	22	10.5	N/A	1
Drilling	CB65-DR2	CB65	31	24	N/A	1
Counterboring	CB65-CB	CB65	14	40	N/A	1
Reaming	CB65-R	CB65	31	25	0.5	1
Reaming	TH1-R	TH1	22	11.5	0.5	1
Reaming	TH2-R	TH2	22	11.5	0.5	1
Reaming	TH3-R	TH3	22	11.5	0.5	1
Reaming	TH4-R	TH4	22	11.5	0.5	1
Bottom and Side Finish Milling	SQ1-BSFM-F	SQ1	160	5	1	1
Bottom and Side Finish Milling	SQ2-BSFM-F	SQ2	25	3	1	1
Bottom and Side Finish Milling	SQ3-BSFM-F	SQ3	25	3	1	1
Bottom and Side Finish Milling	SQ4-BSFM-F	SQ4	25	3	1	1
Bottom and Side Finish Milling	SQ5-BSFM-F	SQ5	25	3	1	1

Table A.7 Machining Parameters for Retaining Cap

Operation Id	Cutting Speed	Feed Rate	Feed Speed	RPM	Machined Time	Removal Rate	Machining Power
-	m/min	mm/r	mm/min	Rpm	min	mm ³ /min	Kw
SQ1-BSRM-R	30.89	0.051	33.63	218	4.61	6,054.17	0.363
SQ2-BSRM-R	30.11	0.049	63.79	436	0.78	9,122.50	0.547
SQ3-BSRM-R	30.11	0.049	63.79	436	0.78	9,122.50	0.547
SQ4-BSRM-R	30.11	0.049	63.79	436	0.78	9,122.50	0.547
SQ5-BSRM-R	30.11	0.049	63.79	436	0.78	9,122.50	0.547
CB65-CDR	30.75	0.351	419.65	294	0.01	22,161.57	1.33
TH1-CDR	31.14	0.288	751.01	609	0	8,517.34	0.511
TH2-CDR	31.14	0.288	751.01	609	0	8,517.34	0.511
TH3-CDR	31.14	0.288	751.01	609	0	8,517.34	0.511
TH4-CDR	31.14	0.288	751.01	609	0	8,517.34	0.511
CB65-DR1	19.64	0.33	165.03	500	0.19	20,251.90	1.215
TH1-DR1	20.1	0.289	175.94	609	0.13	15,234.40	0.914
TH2-DR1	20.1	0.289	175.94	609	0.13	15,234.40	0.914
TH3-DR1	20.1	0.289	175.94	609	0.13	15,234.40	0.914
TH4-DR1	20.1	0.289	175.94	609	0.13	15,234.40	0.914
CB65-DR2	19.64	0.447	116.3	260	0.27	38,342.16	2.301
CB65-CB	20.54	0.523	85.32	163	0.16	68,615.90	4.117
CB65-R	19.64	0.447	111.83	250	0.28	4,303.77	0.258
TH1-R	19.67	0.306	166.25	544	0.13	2,872.60	0.172
TH2-R	19.67	0.306	166.25	544	0.13	2,872.60	0.172
TH3-R	19.67	0.306	166.25	544	0.13	2,872.60	0.172
TH4-R	19.67	0.306	166.25	544	0.13	2,872.60	0.172
SQ1-BSFM-F	30.11	0.049	28.09	192	5.7	140.46	0.008
SQ2-BSFM-F	30.11	0.049	56.04	383	0.45	168.12	0.01
SQ3-BSFM-F	30.11	0.049	56.04	383	0.45	168.12	0.01
SQ4-BSFM-F	30.11	0.049	56.04	383	0.45	168.12	0.01
SQ5-BSFM-F	30.11	0.049	56.04	383	0.45	168.12	0.01

Table A.8 Cutting Tools for Retaining Cap

Operation Id	Tool Name	Tool Id	Tool Diameter	Flute Length	Tool Material
-	-	-	mm	mm	-
SQ1-BSRM-R	End Mill	SEM-22	45	155	HSS
SQ2-BSRM-R	End Mill	SEM-16	22	104	HSS
SQ3-BSRM-R	End Mill	SEM-16	22	104	HSS
SQ4-BSRM-R	End Mill	SEM-16	22	104	HSS
SQ5-BSRM-R	End Mill	SEM-16	22	104	HSS
CB65-CDR	Center Drill	CD-23	8.2	0	HSS
TH1-CDR	Center Drill	CD-5	3.8	0	HSS
TH2-CDR	Center Drill	CD-5	3.8	0	HSS
TH3-CDR	Center Drill	CD-5	3.8	0	HSS
TH4-CDR	Center Drill	CD-5	3.8	0	HSS
CB65-DR1	Twist Drill	TWD-39	12.5	182	HSS
TH1-DR1	Twist Drill	TWD-31	10.5	168	HSS
TH2-DR1	Twist Drill	TWD-31	10.5	168	HSS
TH3-DR1	Twist Drill	TWD-31	10.5	168	HSS
TH4-DR1	Twist Drill	TWD-31	10.5	168	HSS
CB65-DR2	Twist Drill	TWD-85	24	281	HSS
CB65-CB	Counterbore	CB-133	40	0	HSS
CB65-R	Reamer	RM-89	25	0	HSS
TH1-R	Reamer	RM-35	11.5	0	HSS
TH2-R	Reamer	RM-35	11.5	0	HSS
TH3-R	Reamer	RM-35	11.5	0	HSS
TH4-R	Reamer	RM-35	11.5	0	HSS
SQ1-BSFM-F	End Mill	SEM-22	50	177	HSS
SQ2-BSFM-F	End Mill	SEM-16	25	121	HSS
SQ3-BSFM-F	End Mill	SEM-16	25	121	HSS
SQ4-BSFM-F	End Mill	SEM-16	25	121	HSS
SQ5-BSFM-F	End Mill	SEM-16	25	121	HSS

A3. Retaining Cap Example

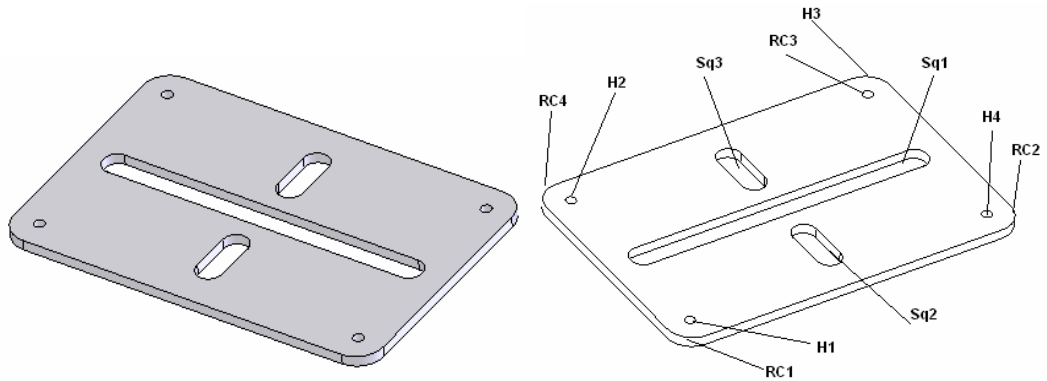


Figure A.3 Offset plate model

Table A.9 Machining Features List for Offset Plate

Feature name	Feature id	Feature size	Location	Orientation
Block base shape, L= 147, W= 96, h=4				
Round hole	H1	D= 4, L=4	x=60, y=60, z=29	XY-top
Round hole	H2	D= 4, L=4	x=60, y=136, z=29	XY-top
Round hole	H3	D= 4, L=4	x=187, y=136, z=29	XY-top
Round hole	H4	D= 4, L=4	x=187, y=60, z=29	XY-top
Square slot	Sq1	L=127, W=10, h=4	x=123, y=98, z=29	XY-top
Square slot	Sq2	L=25, W=10, h=4	x=123, y=74, z=29	XY-top
Square slot	Sq3	L=25, W=10, h=4	x=123, y=122, z=29	XY-top
Edge round	RC1	L= 4, R=10	x=50, y=50, z=27	YZ-right
Edge round	RC2	L= 4, R=10	x=50, y=146, z=27	YZ-right
Edge round	RC3	L= 4, R=10	x=197, y=146, z=27	YZ-left

Table A.10 Machining Operations for Offset Plate

Operation Name	Operation Id	Feature Id	Length	Width	Depth	Passes
-	-	-	mm	mm	mm	-
Side Rough Milling	RC3-SRM-R	RC3	18.24	7.85	2.93	1
Side Rough Milling	RC4-SRM-R	RC4	18.24	7.85	2.93	1
Side Rough Milling	RC1-SRM-R	RC1	18.24	7.85	2.93	1
Side Rough Milling	RC2-SRM-R	RC2	18.24	7.85	2.93	1
Bottom and Side Rough Milling	Sq1-BSRM-R	Sq1	119	8	3	1
Bottom and Side Rough Milling	Sq2-BSRM-R	Sq2	17	8	3	1
Bottom and Side Rough Milling	Sq3-BSRM-R	Sq3	17	8	3	1
Drilling	H1-DR1	H1	10	4	N/A	1
Drilling	H2-DR1	H2	10	4	N/A	1
Drilling	H3-DR1	H3	10	4	N/A	1
Drilling	H4-DR1	H4	10	4	N/A	1
Bottom and Side Finish Milling	Sq1-BSFM-F	Sq1	117	2	1	1
Bottom and Side Finish Milling	Sq2-BSFM-F	Sq2	15	2	1	1
Bottom and Side Finish Milling	Sq3-BSFM-F	Sq3	15	2	1	1

Table A.11 Machining Parameters for Offset Plate

Operation Id	Cutting Speed	Feed Rate	Feed Speed	RPM	Machined Time	Removal Rate	Machining Power
-	m/min	mm/r	mm/min	Rpm	min	mm ³ /min	Kw
RC3-SRM-R	37.48	0.255	212.51	119	0.09	4,888.58	0.293
RC4-SRM-R	37.48	0.255	212.51	119	0.09	4,888.58	0.293
RC1-SRM-R	37.48	0.255	212.51	119	0.09	4,888.58	0.293
RC2-SRM-R	37.48	0.255	212.51	119	0.09	4,888.58	0.293
Sq1-BSRM-R	20.65	0.056	137.31	822	0.87	3,295.47	0.198
Sq2-BSRM-R	20.65	0.056	137.31	822	0.12	3,295.47	0.198
Sq3-BSRM-R	20.65	0.056	137.31	822	0.12	3,295.47	0.198
H1-DR1	18.03	0.107	153.75	435	0.07	1,932.08	0.116
H2-DR1	18.03	0.107	153.75	435	0.07	1,932.08	0.116
H3-DR1	18.03	0.107	153.75	435	0.07	1,932.08	0.116
H4-DR1	18.03	0.107	153.75	435	0.07	1,932.08	0.116
Sq1-BSFM-F	20.65	0.056	109.75	657	1.07	219.5	0.013
Sq2-BSFM-F	20.65	0.056	109.75	657	0.14	219.5	0.013
Sq3-BSFM-F	20.65	0.056	109.75	657	0.14	219.5	0.013

Table A.12 Cutting Tools for Offset Plate

Operation Id	Tool Name	Tool Id	Tool Diameter	Flute Length	Tool Material
-	-	-	mm	mm	-
RC3-SRM-R	Rounding Corner Mill	RCM-13	100	0	HSS
RC4-SRM-R	Rounding Corner Mill	RCM-13	100	0	HSS
RC1-SRM-R	Rounding Corner Mill	RCM-13	100	0	HSS
RC2-SRM-R	Rounding Corner Mill	RCM-13	100	0	HSS
Sq1-BSRM-R	End Mill	SEM-9	8	69	HSS
Sq2-BSRM-R	End Mill	SEM-9	8	69	HSS
Sq3-BSRM-R	End Mill	SEM-9	8	69	HSS
H1-DR1	Twist Drill	TWD-5	4	123	HSS
H2-DR1	Twist Drill	TWD-5	4	123	HSS
H3-DR1	Twist Drill	TWD-5	4	123	HSS
H4-DR1	Twist Drill	TWD-5	4	123	HSS
Sq1-BSFM-F	End Mill	SEM-10	10	72	HSS
Sq2-BSFM-F	End Mill	SEM-10	10	72	HSS
Sq3-BSFM-F	End Mill	SEM-10	10	72	HSS

APPENDIX B

STEP-FM OUTPUT DATA

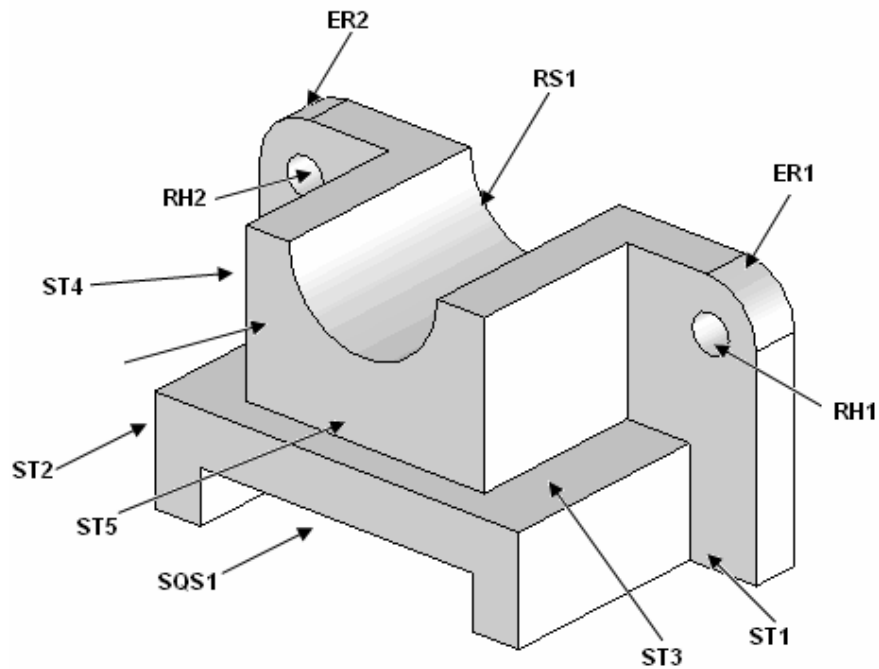


Figure B.1 STEP-FM model example

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          <person_name></person_name>
          <person_address></person_address>
          <person_phone_number></person_phone_number>
        </person>
        <organization>
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          <organization_name></organization_name>
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        </organization>
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        <approval_date></approval_date>
      </release_authorization>
    </initiated_order>
  </customer_order>
</administrative_data>
</block_base_shape>
</placement>

```

```

</release_authorization>
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  <part_name>Auger Support</part_name>
  <part_revision_id>1</part_revision_id>
  <part_description>Support block</part_description>
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    <person_address>No</person_address>
    <person_phone_number>No</person_phone_number>
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    <person_name>Saleh AMAITIK</person_name>
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    </surface_property>
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  <required_delivery_date>25</required_delivery_date>
  <requisition_type>material_requisition</requisition_type>
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      <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
      <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
    </axes>
  </placement>
  <!-- Step Feature Definition -->
  <step id="ST1">
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    <height>50</height>
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    <removal_boundary>
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        <tilt_angle>0</tilt_angle>
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  <its_tolerance>

```

```

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  <property_characteristic>
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    <process_property>
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      <parameter_name></parameter_name>
    </process_property>
    <surface_property>
      <parameter_name></parameter_name>
    </surface_property>
  </property_characteristic>
</its_property>
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<machining_feature>
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  <placement>
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      <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
      <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
    </axes>
  </placement>
  <!-- Step Feature Definition -->
  <step id="ST2">
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    <height>50</height>
    <width>13.4</width>
    <removal_boundary>
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        <profile_radius>0</profile_radius>
        <tilt_angle>0</tilt_angle>
        <profile_angle>90</profile_angle>
      </vee_profile>
    </removal_boundary>
  </step>
  <its_tolerance>
</its_tolerance>
  <its_property>
    <!-- Feature Property -->
    <property_characteristic>
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      <process_property>
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        <parameter_name></parameter_name>
      </process_property>
      <surface_property>
        <parameter_name></parameter_name>
      </surface_property>
    </property_characteristic>
  </its_property>

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```

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    </axes>
  </placement>
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        <tilt_angle>0</tilt_angle>
        <profile_angle>90</profile_angle>
      </vee_profile>
    </removal_boundary>
  </step>
  <its_tolerance>
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    </flatness_tolerance>
  </its_tolerance>
  <its_property>
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    <property_characteristic>
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      <process_property>
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        <parameter_name>--</parameter_name>
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      <surface_property>
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        <parameter_value>2.2</parameter_value>
        <parameter_unit>micro meter</parameter_unit>
        <surface_finish>true</surface_finish>
      </surface_property>
    </property_characteristic>
  </its_property>
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<machining_feature>

```

```

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    <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
    <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
  </axes>
</placement>
<!-- Step Feature Definition -->
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  <length>40</length>
  <height>30</height>
  <width>13.4</width>
  <removal_boundary>
    <vee_profile>
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      <tilt_angle>0</tilt_angle>
      <profile_angle>90</profile_angle>
    </vee_profile>
  </removal_boundary>
</step>
<its_tolerance>
  <!-- Geomtric Tolerance -->
  <flatness_tolerance>
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    <geometric_tolerance_value>0.1</geometric_tolerance_value>
  </flatness_tolerance>
</its_tolerance>
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  <!-- Feature Property -->
  <property_characteristic>
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    <process_property>
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      <parameter_name>--</parameter_name>
      <parameter_type>descriptive_parameter</parameter_type>
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      <parameter_unit>micro meter</parameter_unit>
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</machining_feature>
<machining_feature>
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```

```

</location x="102.2" y="150.8" z="135"/>
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  <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
</axes>
</placement>
<!-- Step Feature Definition -->
<step id="ST5">
  <length>4.6</length>
  <height>30</height>
  <width>48.5</width>
  <removal_boundary>
    <vee_profile>
      <profile_radius>0</profile_radius>
      <tilt_angle>0</tilt_angle>
      <profile_angle>90</profile_angle>
    </vee_profile>
  </removal_boundary>
</step>
<its_tolerance>
</its_tolerance>
<its_property>
  <!-- Feature Property -->
  <property_characteristic>
    <property_name></property_name>
    <process_property>
      <process_name></process_name>
      <parameter_name></parameter_name>
    </process_property>
    <surface_property>
      <parameter_name></parameter_name>
    </surface_property>
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</machining_feature>
<machining_feature>
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      <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
      <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
    </axes>
  </placement>
  <!-- Round Slot Feature Definition -->
  <slot id="RS1">
    <end_condition>
      <first_end_condition>
        <open_slot_end_type/>
      </first_end_condition>
      <second_end_condition>

```



```

        <open_slot_end_type/>
    </second_end_condition>
</end_condition>
<course_of_travel distance="44.75">
</course_of_travel>
<rounded_u_profile>
    <width>28</width>
</rounded_u_profile>
</slot>
<its_tolerance>
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    <cylindricity_tolerance>
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        <geometric_tolerance_value>0.15</geometric_tolerance_value>
    </cylindricity_tolerance>
</its_tolerance>
<its_property>
    <!-- Feature Property -->
    <property_characteristic>
        <property_name></property_name>
        <process_property>
            <process_name></process_name>
            <parameter_name></parameter_name>
        </process_property>
        <surface_property>
            <parameter_name></parameter_name>
        </surface_property>
    </property_characteristic>
</its_property>
</machining_feature>
<machining_feature>
    <usage_name>Corner Support</usage_name>
    <placement>
        <location x="144.5" y="100" z="150"/>
        <axes>
            <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
            <y_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
            <z_axis x_direction_ratio="0" y_direction_ratio="-1" z_direction_ratio="0"/>
        </axes>
    </placement>
    <!-- Edge Round Feature Definition -->
    <edge_round id="ER1" radius="10">
        <length distance="9">
        </length>
    </edge_round>
    <its_tolerance>
        <!-- Size Tolerance -->
        <radial_dimension_tolerance>
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            <units_of_measure>milli meter</units_of_measure>
            <significant_digits>3</significant_digits>
            <dimension_description>Corner Radius</dimension_description>
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    </its_tolerance>

```

```

        <tolerance_value>
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                <lower_limit>0</lower_limit>
                <significant_digits>0</significant_digits>
            </plus_minus_value>
        </tolerance_value>
    </radial_dimension_tolerance>
</its_tolerance>
<its_property>
    <!-- Feature Property -->
    <property_characteristic>
        <property_name></property_name>
        <process_property>
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            <parameter_name></parameter_name>
        </process_property>
        <surface_property>
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        </surface_property>
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</its_property>
</machining_feature>
<machining_feature>
    <usage_name>Corner Support</usage_name>
    <placement>
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        <axes>
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            <y_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="-1"/>
            <z_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        </axes>
    </placement>
    <!-- Edge Round Feature Definition -->
    <edge_round id="ER2" radius="10">
        <length distance="9">
            </length>
        </edge_round>
        <its_tolerance>
            <!-- Size Tolerance -->
            <radial_dimension_tolerance>
                <dimension_value>10</dimension_value>
                <units_of_measure>milli meter</units_of_measure>
                <significant_digits>3</significant_digits>
                <dimension_description>Corner Radius</dimension_description>
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                        <significant_digits>0</significant_digits>
                    </plus_minus_value>
                </tolerance_value>
            </radial_dimension_tolerance>

```

```

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    </process_property>
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    </surface_property>
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</its_property>
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<machining_feature>
  <usage_name>Support</usage_name>
  <placement>
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    <axes>
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      <z_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
    </axes>
  </placement>
  <!-- Round Hole Feature Definition -->
  <round_hole id="RH1">
    <bottom_condition>
      <through_bottom_condition/>
    </bottom_condition>
    <diameter>
      <circular_closed_profile diameter="7.5"/>
    </diameter>
    <hole_depth distance="9">
    </hole_depth>
  </round_hole>
  <its_tolerance>
    <!-- Size Tolerance -->
    <diameter_dimension_tolerance>
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      <units_of_measure>milli meter</units_of_measure>
      <significant_digits>3</significant_digits>
      <dimension_description>Hole Diameter</dimension_description>
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          <lower_range>7.5</lower_range>
          <significant_digits>0</significant_digits>
        </tolerance_range>
      </tolerance_value>
    </diameter_dimension_tolerance>
  </its_tolerance>
</its_property>

```

```

    <!-- Feature Property -->
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      <process_property>
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      </process_property>
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        <parameter_name></parameter_name>
      </surface_property>
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  </its_property>
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<machining_feature>
  <usage_name>Support</usage_name>
  <placement>
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      <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
      <z_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
    </axes>
  </placement>
  <!-- Round Hole Feature Definition -->
  <round_hole id="RH2">
    <bottom_condition>
      <through_bottom_condition/>
    </bottom_condition>
    <diameter>
      <circular_closed_profile diameter="7.5"/>
    </diameter>
    <hole_depth distance="9">
    </hole_depth>
  </round_hole>
  <its_tolerance>
    <!-- Size Tolerance -->
    <diameter_dimension_tolerance>
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      <significant_digits>3</significant_digits>
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      </tolerance_value>
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  </its_tolerance>
  <its_property>
    <!-- Feature Property -->
    <property_characteristic>

```

```

        <property_name></property_name>
        <process_property>
            <process_name></process_name>
            <parameter_name></parameter_name>
        </process_property>
        <surface_property>
            <parameter_name></parameter_name>
        </surface_property>
    </property_characteristic>
</its_property>
</machining_feature>
<machining_feature>
    <usage_name>No Uasge</usage_name>
    <placement>
        <location x="124.5" y="150.8" z="100"/>
        <axes>
            <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
            <y_axis x_direction_ratio="0" y_direction_ratio="-1" z_direction_ratio="0"/>
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        </axes>
    </placement>
    <!-- Square Slot Feature Definition -->
    <slot id="SQS1">
        <end_condition>
            <first_end_condition>
                <open_slot_end_type/>
            </first_end_condition>
            <second_end_condition>
                <open_slot_end_type/>
            </second_end_condition>
        </end_condition>
        <course_of_travel distance="49">
        </course_of_travel>
        <square_u_profile>
            <first_angle>0</first_angle>
            <first_radius>0</first_radius>
            <second_angle>0</second_angle>
            <second_radius>0</second_radius>
            <width>56</width>
            <depth>10</depth>
        </square_u_profile>
    </slot>
    <its_tolerance>
        <!-- Geomtric Tolerance -->
        <perpendicularity_tolerance>
            <significant_digits>3</significant_digits>
            <unit_of_measure>Milli meter</unit_of_measure>
            <geometric_tolerance_value>0.15</geometric_tolerance_value>
            <!-- Datum Definition -->
            <datum name="Dat-A" precedence="1">
                <datum_feature>
                    <planar_element>
                        <location x="24.5" y="50.8" z="10"/>

```

```

        <direction x_ratio="0" y_ratio="0" z_ratio= "-1"/>
    </planar_element>
</datum_feature>
</datum>
</perpendicularity_tolerance>
</its_tolerance>
<its_property>
    <!-- Feature Property -->
    <property_characteristic>
        <property_name>Finishing</property_name>
        <process_property>
            <process_name>finishing</process_name>
            <parameter_name>-</parameter_name>
            <parameter_type>descriptive_parameter</parameter_type>
            <descriptive_string>No Description</descriptive_string>
        </process_property>
        <surface_property>
            <parameter_name>Surface finish</parameter_name>
            <parameter_type>numeric_parameter</parameter_type>
            <parameter_value>2.2</parameter_value>
            <parameter_unit>micro meter</parameter_unit>
            <surface_finish>true</surface_finish>
        </surface_property>
    </property_characteristic>
</its_property>
</machining_feature>
</part>
</STEP-XML>

```

APPENDIX C

ST-FeatCAPP DIGITAL PROCESS PLAN

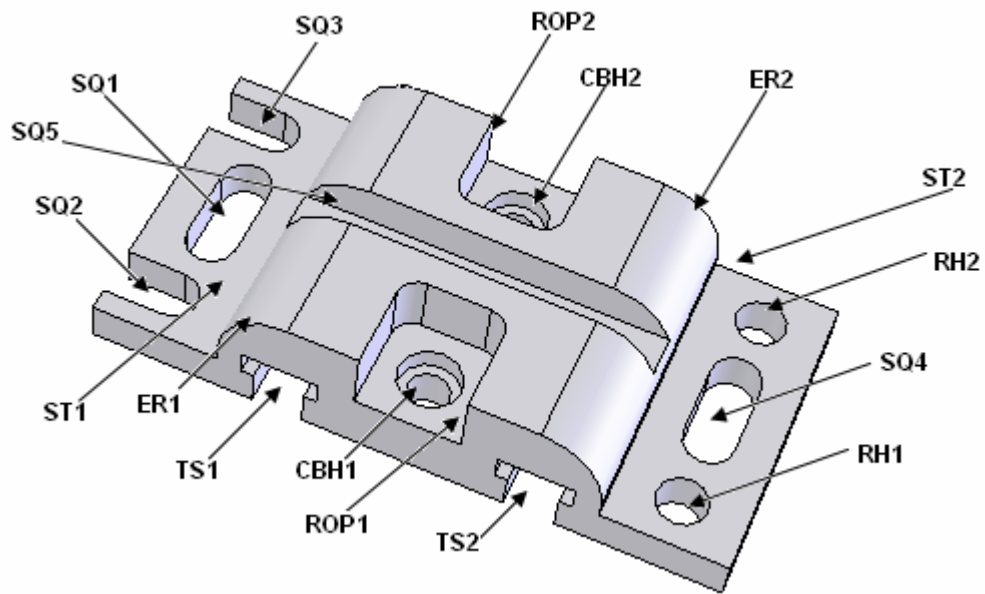


Figure C.1 Process planning example part

```
<STEP-XML xmlc="ISO 10303-28">
  <file_schema>integrated_cnc_schema</file_schema>
  <file_description>ISO14649 file</file_description>
  <file_name>example</file_name>
  <project its_id="Example - 1">
    <its_workpiece>
      <part its_name="Clamping Plate">
        <its_material>
          <material_id>Carbon steel</material_id>
          <material_description>Medium Carbon Steel</material_description>
          <material_hardness>
            <scale>BHN</scale>
            <high_value>350</high_value>
            <low_value>150</low_value>
            <nominal>250</nominal>
          </material_hardness>
        </its_material>
        <!-- Workpiece Raw Material -->
      </part>
    </its_workpiece>
  </project>
</STEP-XML>
```

```

<its_rawpiece>
  <its_material>
    <material_id>Carbon steel</material_id>
    <material_description>Medium Carbon Steel</material_description>
    <material_hardness>
      <scale>BHN</scale>
      <high_value>350</high_value>
      <low_value>150</low_value>
      <nominal>250</nominal>
    </material_hardness>
  </its_material>
  <stock_size L="150" W="75" H="30"/>
</its_rawpiece>
<!-- Workpiece Base Geometry -->
<its_geometry>
  <block_base_shape width="75" height="30" length="150">
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        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
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    </placement>
  </block_base_shape>
</its_geometry>
<!-- Workpiece clamping positions -->
</part>
<!-- Part administrative data -->
<administrative_data>
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      <customer_name>Faraj MURAT</customer_name>
      <customer_address>Istanbul</customer_address>
      <customer_phone_number>905357719818</customer_phone_number>
    </customer>
    <organization>
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      <organization_address>Istanbul</organization_address>
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</quantity_ordered>
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      <person_name>Saleh AMAITIK</person_name>
      <person_address>METU CIM Lab</person_address>
      <person_phone_number>905357719818</person_phone_number>
    </person>
    <organization>
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      <organization_address>Balagat - Ankara- TURKEY</organization_address>
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      <person_phone_number>905357719818</person_phone_number>
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      <organization_name></organization_name>
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  </part_definition>

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            </surface_property>
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<!-- Here come the main process plan-->
<main_workplan>
    <its_elements>
        <!-- Machining Working Step-->

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    <placement>
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        <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="-1"/>
      </axes>
    </placement>
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        <second_end_condition>
          <open_slot_end_type/>
        </second_end_condition>
      </end_condition>
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      <tee_profile>
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        <cross_bar_width>18</cross_bar_width>
        <width>12</width>
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        <second_offset>0</second_offset>
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        <cross_bar_depth>6</cross_bar_depth>
        <radius>0</radius>
      </tee_profile>
    </slot>
    <its_tolerance>
    </its_tolerance>
  </its_feature>
  <its_operation>
    <!-- End milling Machining Operation -->
    <bottom_side_rough_milling its_id="TS1-BSRM-R">
      <overcut_length>6.00</overcut_length>
      <axial_cutting_depth>5.00</axial_cutting_depth>
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      <allowance_bottom>0.00</allowance_bottom>
      <its_machining_strategy>
        <overlap>0.00</overlap>
        <allow_multiple_passes>True</allow_multiple_passes>
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          </feed_direction>
        </unidirectional>
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    </bottom_side_rough_milling>
  </its_operation>
</machining_workingstep>

```

```

        </feed_direction>
        <cutmode>0</cutmode>
    </unidirectional>
</its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
    <endmill its_id="SEM-10">
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        <its_toolbody>
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                <diameter>12.00</diameter>
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                <helix_angle>32.09</helix_angle>
                <radial_rake>8.04</radial_rake>
                <radial_relief>10.42</radial_relief>
                <radial_clearance>15.37</radial_clearance>
                <cutting_edge_angle>0.99</cutting_edge_angle>
                <end_relief>6.00</end_relief>
            </dimension>
        </its_toolbody>
        <its_cutting_edge>
            <its_material>
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                <material_description></material_description>
                <material_hardness>
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                    <low_value>250.00</low_value>
                    <nominal>350.00</nominal>
                </material_hardness>
            </its_material>
        </its_cutting_edge>
    </endmill>
</its_tool>
<its_technology>
    <cutting_speed>19.56</cutting_speed>
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    <feed_speed>75.154</feed_speed>
    <spindle_speed>519</spindle_speed>
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    <depth_of_cut>5.00</depth_of_cut>
    <passes>3</passes>
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    <loops>1</loops>
    <machined_length>87.00</machined_length>
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    <removal_rate>4,509.23</removal_rate>

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    <power_at_spindle>0.27</power_at_spindle>
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  <its_machine_functions>
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    <cutting_fluids>
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        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Heavy_Duty>
        <Sulfurized_Fatty_Soluble_Oil/>
        <Chlorinated_Soluble_Oil/>
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        <Solutions/>
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      </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
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    <mist>False</mist>
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    <chip_removal>False</chip_removal>
  </its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
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<!-- Machining Working Step -->
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  <its_feature>
    <usage_name></usage_name>
    <placement>
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      <axes>
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        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="-1"/>
      </axes>
    </placement>
  <!-- Tee Slot Feature Definition -->
  <slot id="TS2">
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        <open_slot_end_type/>
      </first_end_condition>
      <second_end_condition>
        <open_slot_end_type/>
      </second_end_condition>
    </end_condition>
  </slot id="TS2">
</machining_workingstep>

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</end_condition>
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  <radius>0</radius>
</tee_profile>
</slot>
<its_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_rough_milling its_id="TS2-BSRM-R">
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  <axial_cutting_depth>5.00</axial_cutting_depth>
  <radial_cutting_depth>6.00</radial_cutting_depth>
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  <allowance_bottom>0.00</allowance_bottom>
  <its_machining_strategy>
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    <allow_multiple_passes>True</allow_multiple_passes>
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      <cutmode>0</cutmode>
    </unidirectional>
  </its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
  <endmill its_id="SEM-10">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
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      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
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        <radial_rake>8.04</radial_rake>
        <radial_relief>10.42</radial_relief>
        <radial_clearance>15.37</radial_clearance>

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        <cutting_edge_angle>0.99</cutting_edge_angle>
        <end_relief>6.00</end_relief>
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<its_cutting_edge>
    <its_material>
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        <material_hardness>
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            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
        </material_hardness>
    </its_material>
</its_cutting_edge>
</endmill>
</its_tool>
<its_technology>
    <cutting_speed>19.56</cutting_speed>
    <feed_rate>0.000</feed_rate>
    <feed_speed>75.154</feed_speed>
    <spindle_speed>519</spindle_speed>
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    <depth_of_cut>5.00</depth_of_cut>
    <passes>3</passes>
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    <width_of_cut>12.00</width_of_cut>
    <loops>1</loops>
    <machined_length>87.00</machined_length>
    <machined_time>3.47</machined_time>
    <removal_rate>4,509.23</removal_rate>
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    <power_at_motor>0.34</power_at_motor>
    <torque_at_spindle>4.98</torque_at_spindle>
</its_technology>
<its_machine_functions>
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            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
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            <Chlorinated_Soluble_Oil/>
        </Emulsifiable_Oils-Heavy_Duty>
        <Chemicals_and_Synthesis-Light_Duty>
            <Solutions/>
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        </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
</its_machine_functions>

```

```

        </cutting_fluids>
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        <through_pressure>0.00</through_pressure>
        <chip_removal>False</chip_removal>
    </its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step -->
<machining_workingstep>
    <its_id> WS5163</its_id>
    <its_feature>
        <usage_name></usage_name>
        <placement>
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            <axes>
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                <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
                <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="-1"/>
            </axes>
        </placement>
        <!-- Tee Slot Feature Definition -->
        <slot id="TS1">
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                <first_end_condition>
                    <open_slot_end_type/>
                </first_end_condition>
                <second_end_condition>
                    <open_slot_end_type/>
                </second_end_condition>
            </end_condition>
            <course_of_travel distance="75">
            </course_of_travel>
            <tee_profile>
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                <second_angle>0</second_angle>
                <cross_bar_width>18</cross_bar_width>
                <width>12</width>
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                <first_offset>0</first_offset>
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                <radius>0</radius>
            </tee_profile>
        </slot>
        <its_tolerance>
        </its_tolerance>
    </its_feature>
    <its_operation>
    <!-- End milling Machining Operation -->
    <bottom_side_rough_milling its_id="TS1-BSRM-R1">

```



```

<overcut_length>9.00</overcut_length>
<axial_cutting_depth>6.00</axial_cutting_depth>
<radial_cutting_depth>9.00</radial_cutting_depth>
<allowance_side>0.00</allowance_side>
<allowance_bottom>0.00</allowance_bottom>
<its_machining_strategy>
  <overlap>0.00</overlap>
  <allow_multiple_passes>True</allow_multiple_passes>
  <unidirectional>
    <feed_direction>
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    </feed_direction>
    <cutmode>0</cutmode>
  </unidirectional>
</its_machining_strategy>
<!-- T-Slot Mill Cutter -->
<its_tool>
  <t_slot_mill its_id="TSM-4">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>3</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>18.00</diameter>
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        <flute_length>6.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <shank_diameter>12.00</shank_diameter>
        <stem_diameter>8.00</stem_diameter>
        <stem_length>13.00</stem_length>
        <helix_angle>32.01</helix_angle>
        <radial_rake>7.98</radial_rake>
        <radial_relief>9.95</radial_relief>
        <radial_clearance>15.06</radial_clearance>
        <cutting_edge_angle>1.00</cutting_edge_angle>
        <end_relief>5.99</end_relief>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
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        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </t_slot_mill>
</its_tool>

```

```

<its_technology>
  <cutting_speed>19.38</cutting_speed>
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  <spindle_speed>343</spindle_speed>
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  <depth_of_cut>6.00</depth_of_cut>
  <passes>1</passes>
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  <width_of_cut>18.00</width_of_cut>
  <loops>1</loops>
  <machined_length>93.00</machined_length>
  <machined_time>1.94</machined_time>
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  <power_at_motor>0.39</power_at_motor>
  <torque_at_spindle>8.66</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step -->
<machining_workingstep>
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  <its_feature>
    <usage_name></usage_name>
    <placement>
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      <axes>
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        <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="-1"/>
      </axes>
    </placement>
  <!-- Tee Slot Feature Definition -->
  <slot id="TS2">
    <end_condition>
      <first_end_condition>
        <open_slot_end_type/>
      </first_end_condition>
      <second_end_condition>
        <open_slot_end_type/>
      </second_end_condition>
    </end_condition>
  </slot>
</machining_workingstep>

```

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</end_condition>
<course_of_travel distance="75">
</course_of_travel>
<tee_profile>
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  <second_angle>0</second_angle>
  <cross_bar_width>18</cross_bar_width>
  <width>12</width>
  <depth>9</depth>
  <second_offset>0</second_offset>
  <first_offset>0</first_offset>
  <cross_bar_depth>6</cross_bar_depth>
  <radius>0</radius>
</tee_profile>
</slot>
<its_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_rough_milling its_id="TS2-BSRM-R1">
  <overcut_length>9.00</overcut_length>
  <axial_cutting_depth>6.00</axial_cutting_depth>
  <radial_cutting_depth>9.00</radial_cutting_depth>
  <allowance_side>0.00</allowance_side>
  <allowance_bottom>0.00</allowance_bottom>
  <its_machining_strategy>
    <overlap>0.00</overlap>
    <allow_multiple_passes>True</allow_multiple_passes>
    <unidirectional>
      <feed_direction>
        <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
      </feed_direction>
      <cutmode>0</cutmode>
    </unidirectional>
  </its_machining_strategy>
<!-- T-Slot Mill Cutter -->
<its_tool>
  <t_slot_mill its_id="TSM-4">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>3</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>18.00</diameter>
        <tool_length>70.00</tool_length>
        <flute_length>6.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <shank_diameter>12.00</shank_diameter>
        <stem_diameter>8.00</stem_diameter>
        <stem_length>13.00</stem_length>
        <helix_angle>32.01</helix_angle>

```

```

        <radial_rake>7.98</radial_rake>
        <radial_relief>9.95</radial_relief>
        <radial_clearance>15.06</radial_clearance>
        <cutting_edge_angle>1.00</cutting_edge_angle>
        <end_relief>5.99</end_relief>
    </dimension>
</its_toolbody>
<its_cutting_edge>
    <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
            <scale>BHN</scale>
            <high_value>550.00</high_value>
            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
        </material_hardness>
    </its_material>
</its_cutting_edge>
</t_slot_mill>
</its_tool>
<its_technology>
    <cutting_speed>19.38</cutting_speed>
    <feed_rate>0.000</feed_rate>
    <feed_speed>48.020</feed_speed>
    <spindle_speed>343</spindle_speed>
    <total_depth_of_cut>6.00</total_depth_of_cut>
    <depth_of_cut>6.00</depth_of_cut>
    <passes>1</passes>
    <total_width_of_cut>18.00</total_width_of_cut>
    <width_of_cut>18.00</width_of_cut>
    <loops>1</loops>
    <machined_length>93.00</machined_length>
    <machined_time>1.94</machined_time>
    <removal_rate>5,186.16</removal_rate>
    <power_at_spindle>0.31</power_at_spindle>
    <power_at_motor>0.39</power_at_motor>
    <torque_at_spindle>8.66</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
</cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->

```

```

<machining_workingstep>
  <its_id> WS611</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="65" y="87.5" z="45"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
    <!-- Step Feature Definition -->
    <step id="ST1">
      <length>30</length>
      <height>20</height>
      <width>75</width>
      <removal_boundary>
        <vee_profile>
          <profile_radius>0</profile_radius>
          <tilt_angle>0</tilt_angle>
          <profile_angle>90</profile_angle>
        </vee_profile>
      </removal_boundary>
    </step>
    <its_tolerance>
    </its_tolerance>
  </its_feature>
  <its_operation>
    <!-- End milling Machining Operation -->
    <bottom_side_rough_milling its_id="ST1-BSRM-R">
      <overcut_length>20.00</overcut_length>
      <axial_cutting_depth>10.00</axial_cutting_depth>
      <radial_cutting_depth>75.00</radial_cutting_depth>
      <allowance_side>0.00</allowance_side>
      <allowance_bottom>0.00</allowance_bottom>
      <its_machining_strategy>
        <overlap>0.00</overlap>
        <allow_multiple_passes>True</allow_multiple_passes>
        <unidirectional>
          <feed_direction>
            <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
          </feed_direction>
          <cutmode>0</cutmode>
        </unidirectional>
      </its_machining_strategy>
      <!-- Face Mill Cutter -->
      <its_tool>
        <facemill its_id="FM-5">
          <overall_assembly_length>0</overall_assembly_length>
          <its_toolbody>
            <number_of_teeth>4</number_of_teeth>
            <coolant_through_tool>False</coolant_through_tool>
          </its_toolbody>
        </facemill>
      </its_tool>
    </bottom_side_rough_milling>
  </its_operation>
</machining_workingstep>

```

```

    <dimension>
      <diameter>50.00</diameter>
      <tool_length>0.00</tool_length>
      <flute_length>10.00</flute_length>
      <holder_diameter>0.00</holder_diameter>
      <holder_length>0.00</holder_length>
      <shank_diameter>16.00</shank_diameter>
      <helix_angle>32.00</helix_angle>
      <radial_rake>7.98</radial_rake>
      <radial_relief>9.95</radial_relief>
      <radial_clearance>15.02</radial_clearance>
      <cutting_edge_angle>1.00</cutting_edge_angle>
      <end_relief>5.99</end_relief>
    </dimension>
  </its_toolbody>
  <its_cutting_edge>
    <its_material>
      <material_id>HSS</material_id>
      <material_description></material_description>
      <material_hardness>
        <scale>BHN</scale>
        <high_value>550.00</high_value>
        <low_value>250.00</low_value>
        <nominal>350.00</nominal>
      </material_hardness>
    </its_material>
  </its_cutting_edge>
</facemill>
</its_tool>
<its_technology>
  <cutting_speed>20.36</cutting_speed>
  <feed_rate>0.000</feed_rate>
  <feed_speed>27.950</feed_speed>
  <spindle_speed>130</spindle_speed>
  <total_depth_of_cut>20.00</total_depth_of_cut>
  <depth_of_cut>10.00</depth_of_cut>
  <passes>2</passes>
  <total_width_of_cut>75.00</total_width_of_cut>
  <width_of_cut>75.00</width_of_cut>
  <loops>1</loops>
  <machined_length>70.00</machined_length>
  <machined_time>5.01</machined_time>
  <removal_rate>20,962.50</removal_rate>
  <power_at_spindle>1.26</power_at_spindle>
  <power_at_motor>1.57</power_at_motor>
  <torque_at_spindle>92.39</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>

```

```

        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Light_Duty>
        <Soluble_Oil/>
        <Semichemical/>
        <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
</cutting_fluids>
<coolant_pressure>0</coolant_pressure>
<mist>False</mist>
<through_spindle_coolant>False</through_spindle_coolant>
<through_pressure>0.00</through_pressure>
<chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS622</its_id>
    <its_feature>
        <usage_name></usage_name>
        <placement>
            <location x="185" y="87.5" z="45"/>
            <axes>
                <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
                <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
                <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
            </axes>
        </placement>
        <!-- Step Feature Definition -->
        <step id="ST2">
            <length>30</length>
            <height>20</height>
            <width>75</width>
            <removal_boundary>
                <vee_profile>
                    <profile_radius>0</profile_radius>
                    <tilt_angle>0</tilt_angle>
                    <profile_angle>90</profile_angle>
                </vee_profile>
            </removal_boundary>
        </step>
    </its_feature>
    <its_operation>
<!-- End milling Machining Operation -->

```

```

<bottom_side_rough_milling its_id="ST2-BSRM-R">
  <overcut_length>20.00</overcut_length>
  <axial_cutting_depth>10.00</axial_cutting_depth>
  <radial_cutting_depth>75.00</radial_cutting_depth>
  <allowance_side>0.00</allowance_side>
  <allowance_bottom>0.00</allowance_bottom>
  <its_machining_strategy>
    <overlap>0.00</overlap>
    <allow_multiple_passes>True</allow_multiple_passes>
    <unidirectional>
      <feed_direction>
        <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
      </feed_direction>
      <cutmode>0</cutmode>
    </unidirectional>
  </its_machining_strategy>
  <!-- Face Mill Cutter -->
  <its_tool>
    <facemill its_id="FM-5">
      <overall_assembly_length>0</overall_assembly_length>
      <its_toolbody>
        <number_of_teeth>4</number_of_teeth>
        <coolant_through_tool>False</coolant_through_tool>
        <dimension>
          <diameter>50.00</diameter>
          <tool_length>0.00</tool_length>
          <flute_length>10.00</flute_length>
          <holder_diameter>0.00</holder_diameter>
          <holder_length>0.00</holder_length>
          <shank_diameter>16.00</shank_diameter>
          <helix_angle>32.00</helix_angle>
          <radial_rake>7.98</radial_rake>
          <radial_relief>9.95</radial_relief>
          <radial_clearance>15.02</radial_clearance>
          <cutting_edge_angle>1.00</cutting_edge_angle>
          <end_relief>5.99</end_relief>
        </dimension>
      </its_toolbody>
      <its_cutting_edge>
        <its_material>
          <material_id>HSS</material_id>
          <material_description></material_description>
          <material_hardness>
            <scale>BHN</scale>
            <high_value>550.00</high_value>
            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
          </material_hardness>
        </its_material>
      </its_cutting_edge>
    </facemill>
  </its_tool>
  <its_technology>

```



```

<cutting_speed>20.36</cutting_speed>
<feed_rate>0.000</feed_rate>
<feed_speed>27.950</feed_speed>
<spindle_speed>130</spindle_speed>
<total_depth_of_cut>20.00</total_depth_of_cut>
<depth_of_cut>10.00</depth_of_cut>
<passes>2</passes>
<total_width_of_cut>75.00</total_width_of_cut>
<width_of_cut>75.00</width_of_cut>
<loops>1</loops>
<machined_length>70.00</machined_length>
<machined_time>5.01</machined_time>
<removal_rate>20,962.50</removal_rate>
<power_at_spindle>1.26</power_at_spindle>
<power_at_motor>1.57</power_at_motor>
<torque_at_spindle>92.39</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Light_Duty>
      <Soluble_Oil/>
      <Semichemical/>
      <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
      <Solutions/>
      <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS653</its_id>
  <its_feature>
    <usage_name>Fixing</usage_name>
    <placement>
      <location x="65" y="87.5" z="35"/>
    <axes>

```

```

        <x_axis x_direction_ratio="0" y_direction_ratio="-1" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
    </axes>
</placement>
<!-- Square Slot Feature Definition -->
<slot id="SQ1">
    <end_condition>
        <first_end_condition>
            <radiused_slot_end_type/>
        </first_end_condition>
        <second_end_condition>
            <radiused_slot_end_type/>
        </second_end_condition>
    </end_condition>
    <course_of_travel distance="30">
</course_of_travel>
    <square_u_profile>
        <first_angle>0</first_angle>
        <first_radius>0</first_radius>
        <second_angle>0</second_angle>
        <second_radius>0</second_radius>
        <width>12</width>
        <depth>10</depth>
    </square_u_profile>
</slot>
<its_tolerance>
<!-- Size Tolerance -->
<curved_dimension_tolerance>
    <dimension_value>6</dimension_value>
    <units_of_measure>milli meter</units_of_measure>
    <significant_digits>3</significant_digits>
    <dimension_description>Slot Radius</dimension_description>
    <tolerance_value>
        <plus_minus_value>
            <upper_limit>0.1</upper_limit>
            <lower_limit>0</lower_limit>
            <significant_digits>0</significant_digits>
        </plus_minus_value>
    </tolerance_value>
</curved_dimension_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_rough_milling its_id="SQ1-BSRM-R">
    <overcut_length>0.00</overcut_length>
    <axial_cutting_depth>4.50</axial_cutting_depth>
    <radial_cutting_depth>5.00</radial_cutting_depth>
    <allowance_side>1.00</allowance_side>
    <allowance_bottom>1.00</allowance_bottom>
    <its_machining_strategy>
        <overlap>0.00</overlap>

```

```

<allow_multiple_passes>True</allow_multiple_passes>
<unidirectional>
  <feed_direction>
    <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
  </feed_direction>
  <cutmode>0</cutmode>
</unidirectional>
</its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
  <endmill its_id="SEM-10">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>3</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>10.00</diameter>
        <tool_length>72.00</tool_length>
        <flute_length>22.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <helix_angle>32.09</helix_angle>
        <radial_rake>8.04</radial_rake>
        <radial_relief>10.42</radial_relief>
        <radial_clearance>15.37</radial_clearance>
        <cutting_edge_angle>0.99</cutting_edge_angle>
        <end_relief>6.00</end_relief>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </endmill>
</its_tool>
<its_technology>
  <cutting_speed>19.76</cutting_speed>
  <feed_rate>0.000</feed_rate>
  <feed_speed>93.755</feed_speed>
  <spindle_speed>629</spindle_speed>
  <total_depth_of_cut>9.00</total_depth_of_cut>
  <depth_of_cut>4.50</depth_of_cut>
  <passes>2</passes>
  <total_width_of_cut>10.00</total_width_of_cut>
  <width_of_cut>10.00</width_of_cut>

```

```

    <loops>1</loops>
    <machined_length>20.00</machined_length>
    <machined_time>0.43</machined_time>
    <removal_rate>4,218.98</removal_rate>
    <power_at_spindle>0.25</power_at_spindle>
    <power_at_motor>0.32</power_at_motor>
    <torque_at_spindle>3.84</torque_at_spindle>
  </its_technology>
  <its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
      <Oils-Light_Duty>
        <Straight_Mineral_Oil/>
        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Light_Duty>
        <Soluble_Oil/>
        <Semicheical/>
        <Semisynthetic/>
      </Emulsifiable_Oils-Light_Duty>
      <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
      </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
  </its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS664</its_id>
  <its_feature>
    <usage_name>Fixing</usage_name>
    <placement>
      <location x="60" y="61.25" z="35"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
  <!-- Square Slot Feature Definition -->
  <slot id="SQ2">
    <end_condition>
      <first_end_condition>

```

```

        <open_slot_end_type/>
    </first_end_condition>
    <second_end_condition>
        <radiused_slot_end_type/>
    </second_end_condition>
</end_condition>
<course_of_travel distance="20">
</course_of_travel>
<square_u_profile>
    <first_angle>0</first_angle>
    <first_radius>0</first_radius>
    <second_angle>0</second_angle>
    <second_radius>0</second_radius>
    <width>12</width>
    <depth>10</depth>
</square_u_profile>
</slot>
<its_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_rough_milling its_id="SQ2-BSRM-R">
    <overcut_length>0.00</overcut_length>
    <axial_cutting_depth>5.00</axial_cutting_depth>
    <radial_cutting_depth>6.00</radial_cutting_depth>
    <allowance_side>0.00</allowance_side>
    <allowance_bottom>0.00</allowance_bottom>
    <its_machining_strategy>
        <overlap>0.00</overlap>
        <allow_multiple_passes>True</allow_multiple_passes>
        <unidirectional>
            <feed_direction>
                <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
            </feed_direction>
            <cutmode>0</cutmode>
        </unidirectional>
    </its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
    <endmill its_id="SEM-10">
        <overall_assembly_length>0</overall_assembly_length>
        <its_toolbody>
            <number_of_teeth>3</number_of_teeth>
            <coolant_through_tool>False</coolant_through_tool>
            <dimension>
                <diameter>12.00</diameter>
                <tool_length>83.00</tool_length>
                <flute_length>26.00</flute_length>
                <holder_diameter>0.00</holder_diameter>
                <holder_length>0.00</holder_length>
                <helix_angle>32.09</helix_angle>
                <radial_rake>8.04</radial_rake>
            </dimension>
        </its_toolbody>
    </endmill>
</its_tool>

```

```

        <radial_relief>10.42</radial_relief>
        <radial_clearance>15.37</radial_clearance>
        <cutting_edge_angle>0.99</cutting_edge_angle>
        <end_relief>6.00</end_relief>
    </dimension>
</its_toolbody>
<its_cutting_edge>
    <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
            <scale>BHN</scale>
            <high_value>550.00</high_value>
            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
        </material_hardness>
    </its_material>
</its_cutting_edge>
</endmill>
</its_tool>
<its_technology>
    <cutting_speed>19.56</cutting_speed>
    <feed_rate>0.000</feed_rate>
    <feed_speed>75.154</feed_speed>
    <spindle_speed>519</spindle_speed>
    <total_depth_of_cut>10.00</total_depth_of_cut>
    <depth_of_cut>5.00</depth_of_cut>
    <passes>2</passes>
    <total_width_of_cut>12.00</total_width_of_cut>
    <width_of_cut>12.00</width_of_cut>
    <loops>1</loops>
    <machined_length>20.00</machined_length>
    <machined_time>0.53</machined_time>
    <removal_rate>4,509.23</removal_rate>
    <power_at_spindle>0.27</power_at_spindle>
    <power_at_motor>0.34</power_at_motor>
    <torque_at_spindle>4.98</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
        <Oils-Light_Duty>
            <Straight_Mineral_Oil/>
            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
        <Emulsifiable_Oils-Light_Duty>
            <Soluble_Oil/>
            <Semichemical/>
            <Semisynthetic/>
        </Emulsifiable_Oils-Light_Duty>
        <Chemicals_and_Synthesis-Light_Duty>

```

```

        <Solutions/>
        <Synthetic_Emulsions/>
        </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
    </its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step -->
<machining_workingstep>
    <its_id> WS675</its_id>
    <its_feature>
        <usage_name>Fixing</usage_name>
        <placement>
            <location x="60" y="113.75" z="35"/>
            <axes>
                <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
                <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
                <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
            </axes>
        </placement>
        <!-- Square Slot Feature Definition -->
        <slot id="SQ3">
            <end_condition>
                <first_end_condition>
                    <open_slot_end_type/>
                </first_end_condition>
                <second_end_condition>
                    <radiused_slot_end_type/>
                </second_end_condition>
            </end_condition>
            <course_of_travel distance="20">
        </course_of_travel>
        <square_u_profile>
            <first_angle>0</first_angle>
            <first_radius>0</first_radius>
            <second_angle>0</second_angle>
            <second_radius>0</second_radius>
            <width>12</width>
            <depth>10</depth>
        </square_u_profile>
        </slot>
        <its_tolerance>
        </its_tolerance>
    </its_feature>
    <its_operation>
    <!-- End milling Machining Operation -->
    <bottom_side_rough_milling its_id="SQ3-BSRM-R">

```

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<overcut_length>0.00</overcut_length>
<axial_cutting_depth>5.00</axial_cutting_depth>
<radial_cutting_depth>6.00</radial_cutting_depth>
<allowance_side>0.00</allowance_side>
<allowance_bottom>0.00</allowance_bottom>
<its_machining_strategy>
  <overlap>0.00</overlap>
  <allow_multiple_passes>True</allow_multiple_passes>
  <unidirectional>
    <feed_direction>
      <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
    </feed_direction>
    <cutmode>0</cutmode>
  </unidirectional>
</its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
  <endmill its_id="SEM-10">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>3</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
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        <tool_length>83.00</tool_length>
        <flute_length>26.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <helix_angle>32.09</helix_angle>
        <radial_rake>8.04</radial_rake>
        <radial_relief>10.42</radial_relief>
        <radial_clearance>15.37</radial_clearance>
        <cutting_edge_angle>0.99</cutting_edge_angle>
        <end_relief>6.00</end_relief>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </endmill>
</its_tool>
<its_technology>
  <cutting_speed>19.56</cutting_speed>
  <feed_rate>0.000</feed_rate>

```



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<feed_speed>75.154</feed_speed>
<spindle_speed>519</spindle_speed>
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<depth_of_cut>5.00</depth_of_cut>
<passes>2</passes>
<total_width_of_cut>12.00</total_width_of_cut>
<width_of_cut>12.00</width_of_cut>
<loops>1</loops>
<machined_length>20.00</machined_length>
<machined_time>0.53</machined_time>
<removal_rate>4,509.23</removal_rate>
<power_at_spindle>0.27</power_at_spindle>
<power_at_motor>0.34</power_at_motor>
<torque_at_spindle>4.98</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Light_Duty>
      <Soluble_Oil/>
      <Semichemical/>
      <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
      <Solutions/>
      <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS686</its_id>
  <its_feature>
    <usage_name>Fixing</usage_name>
    <placement>
      <location x="185" y="87.5" z="35"/>
    <axes>
      <x_axis x_direction_ratio="0" y_direction_ratio="-1" z_direction_ratio="0"/>
      <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
    </axes>
  </its_feature>
</machining_workingstep>

```

```

        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
    </axes>
</placement>
<!-- Square Slot Feature Definition -->
<slot id="SQ4">
    <end_condition>
        <first_end_condition>
            <radiused_slot_end_type/>
        </first_end_condition>
        <second_end_condition>
            <radiused_slot_end_type/>
        </second_end_condition>
    </end_condition>
    <course_of_travel distance="30">
</course_of_travel>
    <square_u_profile>
        <first_angle>0</first_angle>
        <first_radius>0</first_radius>
        <second_angle>0</second_angle>
        <second_radius>0</second_radius>
        <width>12</width>
        <depth>10</depth>
    </square_u_profile>
</slot>
<its_tolerance>
<!-- Size Tolerance -->
<curved_dimension_tolerance>
    <dimension_value>6</dimension_value>
    <units_of_measure>milli meter</units_of_measure>
    <significant_digits>3</significant_digits>
    <dimension_description>Slot Radius</dimension_description>
    <tolerance_value>
        <plus_minus_value>
            <upper_limit>0.1</upper_limit>
            <lower_limit>0</lower_limit>
            <significant_digits>0</significant_digits>
        </plus_minus_value>
    </tolerance_value>
</curved_dimension_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_rough_milling its_id="SQ4-BSRM-R">
    <overcut_length>0.00</overcut_length>
    <axial_cutting_depth>4.50</axial_cutting_depth>
    <radial_cutting_depth>5.00</radial_cutting_depth>
    <allowance_side>1.00</allowance_side>
    <allowance_bottom>1.00</allowance_bottom>
    <its_machining_strategy>
        <overlap>0.00</overlap>
        <allow_multiple_passes>True</allow_multiple_passes>
        <unidirectional>

```

```

    <feed_direction>
      <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
    </feed_direction>
    <cutmode>0</cutmode>
  </unidirectional>
</its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
  <endmill its_id="SEM-10">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>3</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>10.00</diameter>
        <tool_length>72.00</tool_length>
        <flute_length>22.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <helix_angle>32.09</helix_angle>
        <radial_rake>8.04</radial_rake>
        <radial_relief>10.42</radial_relief>
        <radial_clearance>15.37</radial_clearance>
        <cutting_edge_angle>0.99</cutting_edge_angle>
        <end_relief>6.00</end_relief>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </endmill>
</its_tool>
<its_technology>
  <cutting_speed>19.76</cutting_speed>
  <feed_rate>0.000</feed_rate>
  <feed_speed>93.755</feed_speed>
  <spindle_speed>629</spindle_speed>
  <total_depth_of_cut>9.00</total_depth_of_cut>
  <depth_of_cut>4.50</depth_of_cut>
  <passes>2</passes>
  <total_width_of_cut>10.00</total_width_of_cut>
  <width_of_cut>10.00</width_of_cut>
  <loops>1</loops>
  <machined_length>20.00</machined_length>

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    <machined_time>0.43</machined_time>
    <removal_rate>4,218.98</removal_rate>
    <power_at_spindle>0.25</power_at_spindle>
    <power_at_motor>0.32</power_at_motor>
    <torque_at_spindle>3.84</torque_at_spindle>
  </its_technology>
  <its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
      <Oils-Light_Duty>
        <Straight_Mineral_Oil/>
        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Light_Duty>
        <Soluble_Oil/>
        <Semichemical/>
        <Semisynthetic/>
      </Emulsifiable_Oils-Light_Duty>
      <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
      </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
  </its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS6117</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="125" y="62.5" z="55"/>
      <axes>
        <x_axis x_direction_ratio="0" y_direction_ratio="-1" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
  <!-- Rectangular Open Pocket Feature Definition -->
  <rectangular_open_pocket id="ROPI">
    <square_u_profile>
      <first_angle>0</first_angle>
      <first_radius>5</first_radius>
      <second_angle>0</second_angle>
    </square_u_profile>
  </rectangular_open_pocket>
</machining_workingstep>

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        <second_radius>5</second_radius>
        <width>25</width>
    </square_u_profile>
    <bottom_condition>
        <planar_pocket_bottom_condition>
            <floor_normal>
                <direction x_ratio="0" y_ratio="0" z_ratio="0"/>
            </floor_normal>
            <floor_location>
                <location x="0" y="0" z="0"/>
            </floor_location>
            <floor_radius>0</floor_radius>
        </planar_pocket_bottom_condition>
    </bottom_condition>
    <pocket_depth distance="15">
</pocket_depth>
    <base_radius>0</base_radius>
</rectangular_open_pocket>
<its_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_rough_milling its_id="ROP1-BSRM-R">
    <overcut_length>0.00</overcut_length>
    <axial_cutting_depth>8.33</axial_cutting_depth>
    <radial_cutting_depth>5.00</radial_cutting_depth>
    <allowance_side>1.00</allowance_side>
    <allowance_bottom>1.00</allowance_bottom>
    <its_machining_strategy>
        <overlap>1.67</overlap>
        <allow_multiple_passes>True</allow_multiple_passes>
        <bidirectional>
            <feed_direction>
                <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
            </feed_direction>
            <stepover_direction>2</stepover_direction>
            <its_stroke_connection_strategy>1</its_stroke_connection_strategy>
        </bidirectional>
    </its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
    <endmill its_id="SEM-9">
        <overall_assembly_length>0</overall_assembly_length>
        <its_toolbody>
            <number_of_teeth>3</number_of_teeth>
            <coolant_through_tool>False</coolant_through_tool>
            <dimension>
                <diameter>10.00</diameter>
                <tool_length>72.00</tool_length>
                <flute_length>22.00</flute_length>
                <holder_diameter>0.00</holder_diameter>
                <holder_length>0.00</holder_length>
            </dimension>
        </its_toolbody>
    </endmill>
</its_tool>

```

```

        <helix_angle>32.09</helix_angle>
        <radial_rake>8.04</radial_rake>
        <radial_relief>10.42</radial_relief>
        <radial_clearance>15.37</radial_clearance>
        <cutting_edge_angle>0.99</cutting_edge_angle>
        <end_relief>6.00</end_relief>
    </dimension>
</its_toolbody>
<its_cutting_edge>
    <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
            <scale>BHN</scale>
            <high_value>550.00</high_value>
            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
        </material_hardness>
    </its_material>
</its_cutting_edge>
</endmill>
</its_tool>
<its_technology>
    <cutting_speed>19.56</cutting_speed>
    <feed_rate>0.000</feed_rate>
    <feed_speed>90.214</feed_speed>
    <spindle_speed>623</spindle_speed>
    <total_depth_of_cut>25.00</total_depth_of_cut>
    <depth_of_cut>5.00</depth_of_cut>
    <passes>5</passes>
    <total_width_of_cut>25.00</total_width_of_cut>
    <width_of_cut>8.33</width_of_cut>
    <loops>3</loops>
    <machined_length>25.00</machined_length>
    <machined_time>4.16</machined_time>
    <removal_rate>3,758.90</removal_rate>
    <power_at_spindle>0.23</power_at_spindle>
    <power_at_motor>0.28</power_at_motor>
    <torque_at_spindle>3.46</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
        <Oils-Light_Duty>
            <Straight_Mineral_Oil/>
            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
        <Emulsifiable_Oils-Light_Duty>
            <Soluble_Oil/>
            <Semichemical/>
            <Semisynthetic/>
        </Emulsifiable_Oils-Light_Duty>
    </cutting_fluids>
</its_machine_functions>

```

```

        </Emulsifiable_Oils-Light_Duty>
        <Chemicals_and_Synthesis-Light_Duty>
            <Solutions/>
            <Synthetic_Emulsions/>
        </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS6128</its_id>
    <its_feature>
        <usage_name></usage_name>
        <placement>
            <location x="125" y="112.5" z="55"/>
            <axes>
                <x_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
                <y_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
                <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
            </axes>
        </placement>
        <!-- Rectangular Open Pocket Feature Definition -->
        <rectangular_open_pocket id="ROP2">
            <square_u_profile>
                <first_angle>0</first_angle>
                <first_radius>5</first_radius>
                <second_angle>0</second_angle>
                <second_radius>5</second_radius>
                <width>25</width>
            </square_u_profile>
            <bottom_condition>
                <planar_pocket_bottom_condition>
                    <floor_normal>
                        <direction x_ratio="0" y_ratio="0" z_ratio="0"/>
                    </floor_normal>
                    <floor_location>
                        <location x="0" y="0" z="0"/>
                    </floor_location>
                    <floor_radius>0</floor_radius>
                </planar_pocket_bottom_condition>
            </bottom_condition>
            <pocket_depth distance="15">
                </pocket_depth>
            <base_radius>0</base_radius>
        </rectangular_open_pocket>
    <its_tolerance>

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```

    </its_tolerance>
  </its_feature>
  <its_operation>
  <!-- End milling Machining Operation -->
  <bottom_side_rough_milling its_id="ROP2-BSRM-R">
    <overcut_length>0.00</overcut_length>
    <axial_cutting_depth>8.33</axial_cutting_depth>
    <radial_cutting_depth>5.00</radial_cutting_depth>
    <allowance_side>1.00</allowance_side>
    <allowance_bottom>1.00</allowance_bottom>
    <its_machining_strategy>
      <overlap>1.67</overlap>
      <allow_multiple_passes>True</allow_multiple_passes>
      <bidirectional>
        <feed_direction>
          <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
        </feed_direction>
        <stepover_direction>2</stepover_direction>
        <its_stroke_connection_strategy>1</its_stroke_connection_strategy>
      </bidirectional>
    </its_machining_strategy>
  <!-- End Mill Cutter -->
  <its_tool>
    <endmill its_id="SEM-9">
      <overall_assembly_length>0</overall_assembly_length>
      <its_toolbody>
        <number_of_teeth>3</number_of_teeth>
        <coolant_through_tool>False</coolant_through_tool>
        <dimension>
          <diameter>10.00</diameter>
          <tool_length>72.00</tool_length>
          <flute_length>22.00</flute_length>
          <holder_diameter>0.00</holder_diameter>
          <holder_length>0.00</holder_length>
          <helix_angle>32.09</helix_angle>
          <radial_rake>8.04</radial_rake>
          <radial_relief>10.42</radial_relief>
          <radial_clearance>15.37</radial_clearance>
          <cutting_edge_angle>0.99</cutting_edge_angle>
          <end_relief>6.00</end_relief>
        </dimension>
      </its_toolbody>
      <its_cutting_edge>
        <its_material>
          <material_id>HSS</material_id>
          <material_description></material_description>
          <material_hardness>
            <scale>BHN</scale>
            <high_value>550.00</high_value>
            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
          </material_hardness>
        </its_material>
      </its_cutting_edge>
    </endmill>
  </its_tool>

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```

        </its_cutting_edge>
    </endmill>
</its_tool>
<its_technology>
    <cutting_speed>19.56</cutting_speed>
    <feed_rate>0.000</feed_rate>
    <feed_speed>90.214</feed_speed>
    <spindle_speed>623</spindle_speed>
    <total_depth_of_cut>25.00</total_depth_of_cut>
    <depth_of_cut>5.00</depth_of_cut>
    <passes>5</passes>
    <total_width_of_cut>25.00</total_width_of_cut>
    <width_of_cut>8.33</width_of_cut>
    <loops>3</loops>
    <machined_length>25.00</machined_length>
    <machined_time>4.16</machined_time>
    <removal_rate>3,758.90</removal_rate>
    <power_at_spindle>0.23</power_at_spindle>
    <power_at_motor>0.28</power_at_motor>
    <torque_at_spindle>3.46</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
        <Oils-Light_Duty>
            <Straight_Mineral_Oil/>
            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
        <Emulsifiable_Oils-Light_Duty>
            <Soluble_Oil/>
            <Semichemical/>
            <Semisynthetic/>
        </Emulsifiable_Oils-Light_Duty>
        <Chemicals_and_Synthesis-Light_Duty>
            <Solutions/>
            <Synthetic_Emulsions/>
        </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS6139</its_id>
    <its_feature>

```

```

<usage_name></usage_name>
<placement>
  <location x="125" y="87.5" z="55"/>
  <axes>
    <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
    <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
    <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
  </axes>
</placement>
<!-- Square Slot Feature Definition -->
<slot id="SQ5">
  <end_condition>
    <first_end_condition>
      <open_slot_end_type/>
    </first_end_condition>
    <second_end_condition>
      <open_slot_end_type/>
    </second_end_condition>
  </end_condition>
  <course_of_travel distance="90">
</course_of_travel>
  <square_u_profile>
    <first_angle>0</first_angle>
    <first_radius>0</first_radius>
    <second_angle>0</second_angle>
    <second_radius>0</second_radius>
    <width>10</width>
    <depth>10</depth>
  </square_u_profile>
</slot>
  <its_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_rough_milling its_id="SQ5-BSRM-R">
  <overcut_length>4.00</overcut_length>
  <axial_cutting_depth>3.00</axial_cutting_depth>
  <radial_cutting_depth>4.00</radial_cutting_depth>
  <allowance_side>1.00</allowance_side>
  <allowance_bottom>1.00</allowance_bottom>
  <its_machining_strategy>
    <overlap>0.00</overlap>
    <allow_multiple_passes>True</allow_multiple_passes>
    <unidirectional>
      <feed_direction>
        <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
      </feed_direction>
      <cutmode>0</cutmode>
    </unidirectional>
  </its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>

```

```

<endmill its_id="SEM-9">
  <overall_assembly_length>0</overall_assembly_length>
  <its_toolbody>
    <number_of_teeth>3</number_of_teeth>
    <coolant_through_tool>False</coolant_through_tool>
    <dimension>
      <diameter>8.00</diameter>
      <tool_length>69.00</tool_length>
      <flute_length>19.00</flute_length>
      <holder_diameter>0.00</holder_diameter>
      <holder_length>0.00</holder_length>
      <helix_angle>32.09</helix_angle>
      <radial_rake>8.04</radial_rake>
      <radial_relief>10.42</radial_relief>
      <radial_clearance>15.37</radial_clearance>
      <cutting_edge_angle>0.99</cutting_edge_angle>
      <end_relief>6.00</end_relief>
    </dimension>
  </its_toolbody>
  <its_cutting_edge>
    <its_material>
      <material_id>HSS</material_id>
      <material_description></material_description>
      <material_hardness>
        <scale>BHN</scale>
        <high_value>550.00</high_value>
        <low_value>250.00</low_value>
        <nominal>350.00</nominal>
      </material_hardness>
    </its_material>
  </its_cutting_edge>
</endmill>
</its_tool>
<its_technology>
  <cutting_speed>20.65</cutting_speed>
  <feed_rate>0.000</feed_rate>
  <feed_speed>137.311</feed_speed>
  <spindle_speed>822</spindle_speed>
  <total_depth_of_cut>9.00</total_depth_of_cut>
  <depth_of_cut>3.00</depth_of_cut>
  <passes>3</passes>
  <total_width_of_cut>8.00</total_width_of_cut>
  <width_of_cut>8.00</width_of_cut>
  <loops>1</loops>
  <machined_length>98.00</machined_length>
  <machined_time>2.14</machined_time>
  <removal_rate>3,295.47</removal_rate>
  <power_at_spindle>0.20</power_at_spindle>
  <power_at_motor>0.25</power_at_motor>
  <torque_at_spindle>2.30</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>

```

```

    <cutting_fluids>
      <Oils-Light_Duty>
        <Straight_Mineral_Oil/>
        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Light_Duty>
        <Soluble_Oil/>
        <Semichemical/>
        <Semisynthetic/>
      </Emulsifiable_Oils-Light_Duty>
      <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
      </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
  </its_machine_functions>
</bottom_side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step -->
<machining_workingstep>
  <its_id> WS6310</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="80" y="87.5" z="55"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
    <!-- Edge Round Feature Definition -->
    <edge_round id="ER1" radius="16">
      <length distance="75">
        </length>
      </edge_round>
      <its_tolerance>
        </its_tolerance>
    </its_feature>
    <its_operation>
      <!-- Side milling Machining Operation -->
      <side_rough_milling its_id="ER1-SRM-R">
        <overcut_length>0.00</overcut_length>
        <axial_cutting_depth>3.31</axial_cutting_depth>
        <radial_cutting_depth>3.31</radial_cutting_depth>
      </side_rough_milling>
    </its_operation>
  </machining_workingstep>
</!-- Machining Working Step -->
</machining_workingstep>

```

```

<allowance_side>0.00</allowance_side>
<its_machining_strategy>
  <overlap>0.00</overlap>
  <allow_multiple_passes>True</allow_multiple_passes>
  <unidirectional>
    <feed_direction>
      <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
    </feed_direction>
    <cutmode>0</cutmode>
  </unidirectional>
</its_machining_strategy>
<!-- Rounding Corner Mill Cutter -->
<its_tool>
  <rounding_corner_mill its_id="RCM-16">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>8</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>125.00</diameter>
        <tool_length>0.00</tool_length>
        <flute_length>24.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <shank_diameter>32.00</shank_diameter>
        <corner_radius>16.00</corner_radius>
        <helix_angle>32.02</helix_angle>
        <radial_rake>7.98</radial_rake>
        <radial_relief>9.95</radial_relief>
        <radial_clearance>15.08</radial_clearance>
        <cutting_edge_angle>1.00</cutting_edge_angle>
        <end_relief>5.98</end_relief>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </rounding_corner_mill>
</its_tool>
<its_technology>
  <cutting_speed>20.05</cutting_speed>
  <feed_rate>0.000</feed_rate>
  <feed_speed>143.940</feed_speed>
  <spindle_speed>51</spindle_speed>

```

```

<total_depth_of_cut>4.69</total_depth_of_cut>
<depth_of_cut>4.69</depth_of_cut>
<passes>1</passes>
<total_width_of_cut>12.57</total_width_of_cut>
<width_of_cut>12.57</width_of_cut>
<loops>1</loops>
<machined_length>95.08</machined_length>
<machined_time>0.66</machined_time>
<removal_rate>8,476.60</removal_rate>
<power_at_spindle>0.51</power_at_spindle>
<power_at_motor>0.64</power_at_motor>
<torque_at_spindle>95.23</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Light_Duty>
      <Soluble_Oil/>
      <Semichemical/>
      <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
      <Solutions/>
      <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS6411</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="170" y="87.5" z="55"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
  </its_feature>
</machining_workingstep>

```

```

</placement>
<!-- Edge Round Feature Definition -->
<edge_round id="ER2" radius="16">
  <length distance="75">
    </length>
  </edge_round>
  <its_tolerance>
  </its_tolerance>
</its_feature>
<its_operation>
<!-- Side milling Machining Operation -->
<side_rough_milling its_id="ER2-SRM-R">
  <overcut_length>0.00</overcut_length>
  <axial_cutting_depth>3.31</axial_cutting_depth>
  <radial_cutting_depth>3.31</radial_cutting_depth>
  <allowance_side>0.00</allowance_side>
  <its_machining_strategy>
    <overlap>0.00</overlap>
    <allow_multiple_passes>True</allow_multiple_passes>
    <unidirectional>
      <feed_direction>
        <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
      </feed_direction>
      <cutmode>0</cutmode>
    </unidirectional>
  </its_machining_strategy>
<!-- Rounding Corner Mill Cutter -->
<its_tool>
  <rounding_corner_mill its_id="RCM-16">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>8</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>125.00</diameter>
        <tool_length>0.00</tool_length>
        <flute_length>24.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <shank_diameter>32.00</shank_diameter>
        <corner_radius>16.00</corner_radius>
        <helix_angle>32.02</helix_angle>
        <radial_rake>7.98</radial_rake>
        <radial_relief>9.95</radial_relief>
        <radial_clearance>15.08</radial_clearance>
        <cutting_edge_angle>1.00</cutting_edge_angle>
        <end_relief>5.98</end_relief>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
      </its_material>
    </its_cutting_edge>
  </rounding_corner_mill>
</its_tool>

```

```

        <material_hardness>
            <scale>BHN</scale>
            <high_value>550.00</high_value>
            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
        </material_hardness>
    </its_material>
</its_cutting_edge>
</rounding_corner_mill>
</its_tool>
<its_technology>
    <cutting_speed>20.05</cutting_speed>
    <feed_rate>0.000</feed_rate>
    <feed_speed>143.940</feed_speed>
    <spindle_speed>51</spindle_speed>
    <total_depth_of_cut>4.69</total_depth_of_cut>
    <depth_of_cut>4.69</depth_of_cut>
    <passes>1</passes>
    <total_width_of_cut>12.57</total_width_of_cut>
    <width_of_cut>12.57</width_of_cut>
    <loops>1</loops>
    <machined_length>95.08</machined_length>
    <machined_time>0.66</machined_time>
    <removal_rate>8,476.60</removal_rate>
    <power_at_spindle>0.51</power_at_spindle>
    <power_at_motor>0.64</power_at_motor>
    <torque_at_spindle>95.23</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
        <Oils-Light_Duty>
            <Straight_Mineral_Oil/>
            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
        <Emulsifiable_Oils-Light_Duty>
            <Soluble_Oil/>
            <Semichemical/>
            <Semisynthetic/>
        </Emulsifiable_Oils-Light_Duty>
        <Chemicals_and_Synthesis-Light_Duty>
            <Solutions/>
            <Synthetic_Emulsions/>
        </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
</its_machine_functions>

```



```

</side_rough_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS6912</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="185" y="61.25" z="35"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
    <!-- Round Hole Feature Definition -->
    <round_hole id="RH1">
      <bottom_condition>
        <through_bottom_condition/>
      </bottom_condition>
      <diameter>
        <circular_closed_profile diameter="12"/>
      </diameter>
      <hole_depth distance="10">
      </hole_depth>
    </round_hole>
    <its_tolerance>
    <!-- Size Tolerance -->
    <diameter_dimension_tolerance>
      <dimension_value>12</dimension_value>
      <units_of_measure>micro meter</units_of_measure>
      <significant_digits>3</significant_digits>
      <dimension_description>Hole Diameter</dimension_description>
      <tolerance_value>
        <plus_minus_value>
          <upper_limit>0.075</upper_limit>
          <lower_limit>0</lower_limit>
          <significant_digits>0</significant_digits>
        </plus_minus_value>
      </tolerance_value>
    </diameter_dimension_tolerance>
    </its_tolerance>
  </its_feature>
  <its_operation>
  <!-- Center Drilling Machining Operation -->
  <center_drilling its_id="RH1-CDR">
    <overcut_length>0.00</overcut_length>
    <cut_depth>3.00</cut_depth>
    <previous_diameter>0.00</previous_diameter>
    <dwelling_time_bottom>5.00</dwelling_time_bottom>
    <feed_on_retract>0.29</feed_on_retract>
    <its_machining_strategy>

```

```

<reduced_cut_at_start>17.02</reduced_cut_at_start>
<reduced_feed_at_start>0.25</reduced_feed_at_start>
<depth_of_start>0.00</depth_of_start>
<reduced_cut_at_end>17.02</reduced_cut_at_end>
<reduced_feed_at_end>0.25</reduced_feed_at_end>
<depth_of_end>0.00</depth_of_end>
</its_machining_strategy>
<!-- Center Drilling Tool -->
<its_tool>
  <center_drill its_id="CD-6">
    <overall_assembly_length>0.00</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>0</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>4.00</diameter>
        <tool_length>0.00</tool_length>
        <flute_length>0.00</flute_length>
        <holder_length>0.00</holder_length>
        <holder_diameter>0.00</holder_diameter>
        <tip_diameter>0.00</tip_diameter>
        <tip_length>0.00</tip_length>
        <tip_angle>0.00</tip_angle>
        <taper_angle>0.00</taper_angle>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </center_drill>
</its_tool>
<its_technology>
  <cutting_speed>20.02</cutting_speed>
  <feed_rate>0.291</feed_rate>
  <feed_speed>464.212</feed_speed>
  <spindle_speed>1593</spindle_speed>
  <depth_of_cut>0.00</depth_of_cut>
  <passes>1</passes>
  <width_of_cut>0.00</width_of_cut>
  <machined_length>3.00</machined_length>
  <machined_diameter>4.00</machined_diameter>
  <machined_time>0.01</machined_time>
  <removal_rate>5,833.46</removal_rate>
  <power_at_spindle>0.35</power_at_spindle>

```

```

    <power_at_motor>0.44</power_at_motor>
    <torque_at_spindle>2.10</torque_at_spindle>
  </its_technology>
  <its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
      <Oils-Light_Duty>
        <Straight_Mineral_Oil/>
        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Light_Duty>
        <Soluble_Oil/>
        <Semichemical/>
        <Semisynthetic/>
      </Emulsifiable_Oils-Light_Duty>
      <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
      </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
  </its_machine_functions>
</center_drilling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step -->
<machining_workingstep>
  <its_id> WS61013</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="185" y="113.75" z="35"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
    <!-- Round Hole Feature Definition -->
    <round_hole id="RH2">
      <bottom_condition>
        <through_bottom_condition/>
      </bottom_condition>
      <diameter>
        <circular_closed_profile diameter="12"/>
      </diameter>
      <hole_depth distance="10">

```

```

    </hole_depth>
</round_hole>
<its_tolerance>
<!-- Size Tolerance -->
<diameter_dimension_tolerance>
  <dimension_value>12</dimension_value>
  <units_of_measure>micro meter</units_of_measure>
  <significant_digits>3</significant_digits>
  <dimension_description>Hole Diameter</dimension_description>
  <tolerance_value>
    <plus_minus_value>
      <upper_limit>0.075</upper_limit>
      <lower_limit>0</lower_limit>
      <significant_digits>0</significant_digits>
    </plus_minus_value>
  </tolerance_value>
</diameter_dimension_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- Center Drilling Machining Operation -->
<center_drilling its_id="RH2-CDR">
  <overcut_length>0.00</overcut_length>
  <cut_depth>3.00</cut_depth>
  <previous_diameter>0.00</previous_diameter>
  <dwell_time_bottom>5.00</dwell_time_bottom>
  <feed_on_retract>0.29</feed_on_retract>
  <its_machining_strategy>
    <reduced_cut_at_start>17.02</reduced_cut_at_start>
    <reduced_feed_at_start>0.25</reduced_feed_at_start>
    <depth_of_start>0.00</depth_of_start>
    <reduced_cut_at_end>17.02</reduced_cut_at_end>
    <reduced_feed_at_end>0.25</reduced_feed_at_end>
    <depth_of_end>0.00</depth_of_end>
  </its_machining_strategy>
  <!-- Center Drilling Tool -->
  <its_tool>
    <center_drill its_id="CD-6">
      <overall_assembly_length>0.00</overall_assembly_length>
      <its_toolbody>
        <number_of_teeth>0</number_of_teeth>
        <coolant_through_tool>False</coolant_through_tool>
        <dimension>
          <diameter>4.00</diameter>
          <tool_length>0.00</tool_length>
          <flute_length>0.00</flute_length>
          <holder_length>0.00</holder_length>
          <holder_diameter>0.00</holder_diameter>
          <tip_diameter>0.00</tip_diameter>
          <tip_length>0.00</tip_length>
          <tip_angle>0.00</tip_angle>
          <taper_angle>0.00</taper_angle>
        </dimension>
      </its_toolbody>
    </center_drill>
  </its_tool>
</center_drilling>

```

```

</its_toolbody>
<its_cutting_edge>
  <its_material>
    <material_id>HSS</material_id>
    <material_description></material_description>
    <material_hardness>
      <scale>BHN</scale>
      <high_value>550.00</high_value>
      <low_value>250.00</low_value>
      <nominal>350.00</nominal>
    </material_hardness>
  </its_material>
</its_cutting_edge>
</center_drill>
</its_tool>
<its_technology>
  <cutting_speed>20.02</cutting_speed>
  <feed_rate>0.291</feed_rate>
  <feed_speed>464.212</feed_speed>
  <spindle_speed>1593</spindle_speed>
  <depth_of_cut>0.00</depth_of_cut>
  <passes>1</passes>
  <width_of_cut>0.00</width_of_cut>
  <machined_length>3.00</machined_length>
  <machined_diameter>4.00</machined_diameter>
  <machined_time>0.01</machined_time>
  <removal_rate>5,833.46</removal_rate>
  <power_at_spindle>0.35</power_at_spindle>
  <power_at_motor>0.44</power_at_motor>
  <torque_at_spindle>2.10</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Light_Duty>
      <Soluble_Oil/>
      <Semicheical/>
      <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
      <Solutions/>
      <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>

```

```

        <through_pressure>0.00</through_pressure>
        <chip_removal>False</chip_removal>
    </its_machine_functions>
</center_drilling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS6914</its_id>
    <its_feature>
        <usage_name></usage_name>
        <placement>
            <location x="185" y="61.25" z="35"/>
            <axes>
                <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
                <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
                <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
            </axes>
        </placement>
        <!-- Round Hole Feature Definition -->
        <round_hole id="RH1">
            <bottom_condition>
                <through_bottom_condition/>
            </bottom_condition>
            <diameter>
                <circular_closed_profile diameter="12"/>
            </diameter>
            <hole_depth distance="10">
            </hole_depth>
        </round_hole>
        <its_tolerance>
            <!-- Size Tolerance -->
            <diameter_dimension_tolerance>
                <dimension_value>12</dimension_value>
                <units_of_measure>micro meter</units_of_measure>
                <significant_digits>3</significant_digits>
                <dimension_description>Hole Diameter</dimension_description>
                <tolerance_value>
                    <plus_minus_value>
                        <upper_limit>0.075</upper_limit>
                        <lower_limit>0</lower_limit>
                        <significant_digits>0</significant_digits>
                    </plus_minus_value>
                </tolerance_value>
            </diameter_dimension_tolerance>
        </its_tolerance>
    </its_feature>
    <its_operation>
        <!-- Drilling Machining Operation -->
        <drilling its_id="RH1-DR1">
            <overcut_length>3.00</overcut_length>
            <cut_depth>13.00</cut_depth>
            <previous_diameter>0.00</previous_diameter>

```

```

<dwel_time_bottom>5.00</dwel_time_bottom>
<feed_on_retract>0.30</feed_on_retract>
<its_machining_strategy>
  <reduced_cut_at_start>16.89</reduced_cut_at_start>
  <reduced_feed_at_start>0.25</reduced_feed_at_start>
  <depth_of_start>0.00</depth_of_start>
  <reduced_cut_at_end>16.89</reduced_cut_at_end>
  <reduced_feed_at_end>0.25</reduced_feed_at_end>
  <depth_of_end>0.00</depth_of_end>
</its_machining_strategy>
<!-- Twist Drilling Tool -->
<its_tool>
  <twist_drill its_id="TWD-33">
    <overall_assembly_length>0.00</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>0</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>11.00</diameter>
        <tool_length>175.00</tool_length>
        <flute_length>94.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <helix_angle>29.47</helix_angle>
        <point_angle>115.09</point_angle>
        <land_width>6.71</land_width>
        <lip_clearance>12.60</lip_clearance>
        <margin_height>0.31</margin_height>
        <margin_width>0.74</margin_width>
        <chisel_edge>130.48</chisel_edge>
        <web_thickness>2.85</web_thickness>
        <back_taper>0.00</back_taper>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </twist_drill>
</its_tool>
<its_technology>
  <cutting_speed>19.87</cutting_speed>
  <feed_rate>0.297</feed_rate>
  <feed_speed>170.724</feed_speed>
  <spindle_speed>575</spindle_speed>

```

```

    <depth_of_cut>0.00</depth_of_cut>
    <passes>1</passes>
    <width_of_cut>0.00</width_of_cut>
    <machined_length>16.00</machined_length>
    <machined_diameter>11.00</machined_diameter>
    <machined_time>0.09</machined_time>
    <removal_rate>16,224.48</removal_rate>
    <power_at_spindle>0.97</power_at_spindle>
    <power_at_motor>1.22</power_at_motor>
    <torque_at_spindle>16.17</torque_at_spindle>
  </its_technology>
  <its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
      <Oils-Light_Duty>
        <Straight_Mineral_Oil/>
        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Light_Duty>
        <Soluble_Oil/>
        <Semichemical/>
        <Semisynthetic/>
      </Emulsifiable_Oils-Light_Duty>
      <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
      </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
  </its_machine_functions>
</drilling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS61015</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="185" y="113.75" z="35"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
  </its_feature>
</machining_workingstep>
<!-- Round Hole Feature Definition -->

```



```

<round_hole id="RH2">
  <bottom_condition>
    <through_bottom_condition/>
  </bottom_condition>
  <diameter>
    <circular_closed_profile diameter="12"/>
  </diameter>
  <hole_depth distance="10">
    </hole_depth>
</round_hole>
<its_tolerance>
<!-- Size Tolerance -->
<diameter_dimension_tolerance>
  <dimension_value>12</dimension_value>
  <units_of_measure>micro meter</units_of_measure>
  <significant_digits>3</significant_digits>
  <dimension_description>Hole Diameter</dimension_description>
  <tolerance_value>
    <plus_minus_value>
      <upper_limit>0.075</upper_limit>
      <lower_limit>0</lower_limit>
      <significant_digits>0</significant_digits>
    </plus_minus_value>
  </tolerance_value>
</diameter_dimension_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- Drilling Machining Operation -->
<drilling its_id="RH2-DR1">
  <overcut_length>3.00</overcut_length>
  <cut_depth>13.00</cut_depth>
  <previous_diameter>0.00</previous_diameter>
  <dwelling_time_bottom>5.00</dwelling_time_bottom>
  <feed_on_retract>0.30</feed_on_retract>
  <its_machining_strategy>
    <reduced_cut_at_start>16.89</reduced_cut_at_start>
    <reduced_feed_at_start>0.25</reduced_feed_at_start>
    <depth_of_start>0.00</depth_of_start>
    <reduced_cut_at_end>16.89</reduced_cut_at_end>
    <reduced_feed_at_end>0.25</reduced_feed_at_end>
    <depth_of_end>0.00</depth_of_end>
  </its_machining_strategy>
<!-- Twist Drilling Tool -->
<its_tool>
  <twist_drill its_id="TWD-33">
    <overall_assembly_length>0.00</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>0</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>11.00</diameter>
        <tool_length>175.00</tool_length>
      </dimension>
    </its_toolbody>
  </twist_drill>
</its_tool>

```

```

        <flute_length>94.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <helix_angle>29.47</helix_angle>
        <point_angle>115.09</point_angle>
        <land_width>6.71</land_width>
        <lip_clearance>12.60</lip_clearance>
        <margin_height>0.31</margin_height>
        <margin_width>0.74</margin_width>
        <chisel_edge>130.48</chisel_edge>
        <web_thickness>2.85</web_thickness>
        <back_taper>0.00</back_taper>
    </dimension>
</its_toolbody>
<its_cutting_edge>
    <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
            <scale>BHN</scale>
            <high_value>550.00</high_value>
            <low_value>250.00</low_value>
            <nominal>350.00</nominal>
        </material_hardness>
    </its_material>
</its_cutting_edge>
</twist_drill>
</its_tool>
<its_technology>
    <cutting_speed>19.87</cutting_speed>
    <feed_rate>0.297</feed_rate>
    <feed_speed>170.724</feed_speed>
    <spindle_speed>575</spindle_speed>
    <depth_of_cut>0.00</depth_of_cut>
    <passes>1</passes>
    <width_of_cut>0.00</width_of_cut>
    <machined_length>16.00</machined_length>
    <machined_diameter>11.00</machined_diameter>
    <machined_time>0.09</machined_time>
    <removal_rate>16,224.48</removal_rate>
    <power_at_spindle>0.97</power_at_spindle>
    <power_at_motor>1.22</power_at_motor>
    <torque_at_spindle>16.17</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
        <Oils-Light_Duty>
            <Straight_Mineral_Oil/>
            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
    </cutting_fluids>
</its_machine_functions>

```

```

    <Emulsifiable_Oils-Light_Duty>
      <Soluble_Oil/>
      <Semichemical/>
      <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
      <Solutions/>
      <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</drilling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS61416</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="125" y="62.5" z="40"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
    <!-- Counterbore Hole Feature Definition -->
    <counterbore_hole id="CBH1">
      <smaller_hole>
        <bottom_condition>
          <through_bottom_condition/>
        </bottom_condition>
        <diameter>
          <circular_closed_profile diameter="10"/>
        </diameter>
        <hole_depth distance="10">
          </hole_depth>
        </smaller_hole>
        <larger_hole>
          <change_in_diameter>
            </change_in_diameter>
          <bottom_condition>
            </bottom_condition>
          <diameter>
            <circular_closed_profile diameter="15"/>
          </diameter>
          <hole_depth distance="5">

```

```

        </hole_depth>
    </larger_hole>
</counterbore_hole>
    <its_tolerance>
    </its_tolerance>
</its_feature>
<its_operation>
<!-- Drilling Machining Operation -->
<drilling its_id="CBH1-DR1">
    <overcut_length>3.00</overcut_length>
    <cut_depth>18.00</cut_depth>
    <previous_diameter>0.00</previous_diameter>
    <dwel_time_bottom>5.00</dwel_time_bottom>
    <feed_on_retract>0.28</feed_on_retract>
    <its_machining_strategy>
        <reduced_cut_at_start>17.31</reduced_cut_at_start>
        <reduced_feed_at_start>0.24</reduced_feed_at_start>
        <depth_of_start>0.00</depth_of_start>
        <reduced_cut_at_end>17.31</reduced_cut_at_end>
        <reduced_feed_at_end>0.24</reduced_feed_at_end>
        <depth_of_end>0.00</depth_of_end>
    </its_machining_strategy>
    <!-- Twist Drilling Tool -->
    <its_tool>
        <twist_drill its_id="TWD-29">
            <overall_assembly_length>0.00</overall_assembly_length>
            <its_toolbody>
                <number_of_teeth>0</number_of_teeth>
                <coolant_through_tool>False</coolant_through_tool>
                <dimension>
                    <diameter>10.00</diameter>
                    <tool_length>168.00</tool_length>
                    <flute_length>87.00</flute_length>
                    <holder_diameter>0.00</holder_diameter>
                    <holder_length>0.00</holder_length>
                    <helix_angle>28.99</helix_angle>
                    <point_angle>114.14</point_angle>
                    <land_width>5.94</land_width>
                    <lip_clearance>12.59</lip_clearance>
                    <margin_height>0.28</margin_height>
                    <margin_width>0.66</margin_width>
                    <chisel_edge>130.17</chisel_edge>
                    <web_thickness>2.67</web_thickness>
                    <back_taper>0.00</back_taper>
                </dimension>
            </its_toolbody>
            <its_cutting_edge>
                <its_material>
                    <material_id>HSS</material_id>
                    <material_description></material_description>
                    <material_hardness>
                        <scale>BHN</scale>
                        <high_value>550.00</high_value>

```

```

        <low_value>250.00</low_value>
        <nominal>350.00</nominal>
    </material_hardness>
</its_material>
    </its_cutting_edge>
</twist_drill>
</its_tool>
<its_technology>
    <cutting_speed>20.36</cutting_speed>
    <feed_rate>0.281</feed_rate>
    <feed_speed>182.121</feed_speed>
    <spindle_speed>648</spindle_speed>
    <depth_of_cut>0.00</depth_of_cut>
    <passes>1</passes>
    <width_of_cut>0.00</width_of_cut>
    <machined_length>21.00</machined_length>
    <machined_diameter>10.00</machined_diameter>
    <machined_time>0.12</machined_time>
    <removal_rate>14,303.78</removal_rate>
    <power_at_spindle>0.86</power_at_spindle>
    <power_at_motor>1.07</power_at_motor>
    <torque_at_spindle>12.65</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
        <Oils-Light_Duty>
            <Straight_Mineral_Oil/>
            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
        <Emulsifiable_Oils-Heavy_Duty>
            <Sulfurized_Fatty_Soluble_Oil/>
            <Chlorinated_Soluble_Oil/>
        </Emulsifiable_Oils-Heavy_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
</its_machine_functions>
</drilling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS61517</its_id>
    <its_feature>
        <usage_name></usage_name>
        <placement>
            <location x="125" y="112.5" z="40"/>

```

```

<axes>
  <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
  <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
  <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
</axes>
</placement>
<!-- Counterbore Hole Feature Definition -->
<counterbore_hole id="CBH2">
  <smaller_hole>
    <bottom_condition>
      <through_bottom_condition/>
    </bottom_condition>
    <diameter>
      <circular_closed_profile diameter="10"/>
    </diameter>
    <hole_depth distance="10">
      </hole_depth>
    </smaller_hole>
    <larger_hole>
      <change_in_diameter>
      </change_in_diameter>
      <bottom_condition>
      </bottom_condition>
      <diameter>
        <circular_closed_profile diameter="15"/>
      </diameter>
      <hole_depth distance="5">
        </hole_depth>
      </larger_hole>
    </counterbore_hole>
    <its_tolerance>
    </its_tolerance>
  </its_feature>
  <its_operation>
  <!-- Drilling Machining Operation -->
  <drilling its_id="CBH2-DR1">
    <overcut_length>3.00</overcut_length>
    <cut_depth>18.00</cut_depth>
    <previous_diameter>0.00</previous_diameter>
    <dwel_time_bottom>5.00</dwel_time_bottom>
    <feed_on_retract>0.28</feed_on_retract>
    <its_machining_strategy>
      <reduced_cut_at_start>17.31</reduced_cut_at_start>
      <reduced_feed_at_start>0.24</reduced_feed_at_start>
      <depth_of_start>0.00</depth_of_start>
      <reduced_cut_at_end>17.31</reduced_cut_at_end>
      <reduced_feed_at_end>0.24</reduced_feed_at_end>
      <depth_of_end>0.00</depth_of_end>
    </its_machining_strategy>
    <!-- Twist Drilling Tool -->
    <its_tool>
      <twist_drill its_id="TWD-29">
        <overall_assembly_length>0.00</overall_assembly_length>

```

```

<its_toolbody>
  <number_of_teeth>0</number_of_teeth>
  <coolant_through_tool>False</coolant_through_tool>
  <dimension>
    <diameter>10.00</diameter>
    <tool_length>168.00</tool_length>
    <flute_length>87.00</flute_length>
    <holder_diameter>0.00</holder_diameter>
    <holder_length>0.00</holder_length>
    <helix_angle>28.99</helix_angle>
    <point_angle>114.14</point_angle>
    <land_width>5.94</land_width>
    <lip_clearance>12.59</lip_clearance>
    <margin_height>0.28</margin_height>
    <margin_width>0.66</margin_width>
    <chisel_edge>130.17</chisel_edge>
    <web_thickness>2.67</web_thickness>
    <back_taper>0.00</back_taper>
  </dimension>
</its_toolbody>
<its_cutting_edge>
  <its_material>
    <material_id>HSS</material_id>
    <material_description></material_description>
    <material_hardness>
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      <high_value>550.00</high_value>
      <low_value>250.00</low_value>
      <nominal>350.00</nominal>
    </material_hardness>
  </its_material>
</its_cutting_edge>
</twist_drill>
</its_tool>
<its_technology>
  <cutting_speed>20.36</cutting_speed>
  <feed_rate>0.281</feed_rate>
  <feed_speed>182.121</feed_speed>
  <spindle_speed>648</spindle_speed>
  <depth_of_cut>0.00</depth_of_cut>
  <passes>1</passes>
  <width_of_cut>0.00</width_of_cut>
  <machined_length>21.00</machined_length>
  <machined_diameter>10.00</machined_diameter>
  <machined_time>0.12</machined_time>
  <removal_rate>14,303.78</removal_rate>
  <power_at_spindle>0.86</power_at_spindle>
  <power_at_motor>1.07</power_at_motor>
  <torque_at_spindle>12.65</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>

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    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Heavy_Duty>
      <Sulfurized_Fatty_Soluble_Oil/>
      <Chlorinated_Soluble_Oil/>
    </Emulsifiable_Oils-Heavy_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</drilling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS61418</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
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      <axes>
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        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
    <!-- Counterbore Hole Feature Definition -->
    <counterbore_hole id="CBH1">
      <smaller_hole>
        <bottom_condition>
          <through_bottom_condition/>
        </bottom_condition>
        <diameter>
          <circular_closed_profile diameter="10"/>
        </diameter>
        <hole_depth distance="10">
          </hole_depth>
        </smaller_hole>
        <larger_hole>
          <change_in_diameter>
            </change_in_diameter>
          <bottom_condition>
            </bottom_condition>
          <diameter>
            <circular_closed_profile diameter="15"/>
          </diameter>
        </larger_hole>
      </counterbore_hole>
    </its_feature>
  </machining_workingstep>
</!-- Machining Working Step-->

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        <hole_depth distance="5">
        </hole_depth>
    </larger_hole>
</counterbore_hole>
    <its_tolerance>
    </its_tolerance>
</its_feature>
<its_operation>
<!-- Counterboring Machining Operation -->
<counterboring its_id="CBH1-CB">
    <overcut_length>0.00</overcut_length>
    <cut_depth>8.00</cut_depth>
    <previous_diameter>10.00</previous_diameter>
    <dwelling_time_bottom>5.00</dwelling_time_bottom>
    <feed_on_retract>0.35</feed_on_retract>
    <its_machining_strategy>
        <reduced_cut_at_start>16.60</reduced_cut_at_start>
        <reduced_feed_at_start>0.29</reduced_feed_at_start>
        <depth_of_start>0.00</depth_of_start>
        <reduced_cut_at_end>16.60</reduced_cut_at_end>
        <reduced_feed_at_end>0.29</reduced_feed_at_end>
        <depth_of_end>0.00</depth_of_end>
    </its_machining_strategy>
<!-- Counterbore Tool -->
<its_tool>
    <counterbore its_id="CB-49">
        <overall_assembly_length>0.00</overall_assembly_length>
        <its_toolbody>
            <number_of_teeth>0</number_of_teeth>
            <coolant_through_tool>False</coolant_through_tool>
            <dimension>
                <diameter>15.00</diameter>
                <tool_length>0.00</tool_length>
                <flute_length>0.00</flute_length>
                <holder_diameter>0.00</holder_diameter>
                <holder_length>0.00</holder_length>
                <shank_diameter>0.00</shank_diameter>
                <tip_length>0.00</tip_length>
            </dimension>
        </its_toolbody>
        <its_cutting_edge>
            <its_material>
                <material_id>HSS</material_id>
                <material_description></material_description>
                <material_hardness>
                    <scale>BHN</scale>
                    <high_value>550.00</high_value>
                    <low_value>250.00</low_value>
                    <nominal>350.00</nominal>
                </material_hardness>
            </its_material>
        </its_cutting_edge>
    </counterbore>

```

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</its_tool>
<its_technology>
  <cutting_speed>19.53</cutting_speed>
  <feed_rate>0.345</feed_rate>
  <feed_speed>142.907</feed_speed>
  <spindle_speed>414</spindle_speed>
  <depth_of_cut>0.00</depth_of_cut>
  <passes>1</passes>
  <width_of_cut>0.00</width_of_cut>
  <machined_length>8.00</machined_length>
  <machined_diameter>15.00</machined_diameter>
  <machined_time>0.06</machined_time>
  <removal_rate>14,029.84</removal_rate>
  <power_at_spindle>0.84</power_at_spindle>
  <power_at_motor>1.05</power_at_motor>
  <torque_at_spindle>19.42</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
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      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Light_Duty>
      <Soluble_Oil/>
      <Semichemical/>
      <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
      <Solutions/>
      <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</counterboring>
</its_operation>
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<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS61519</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
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    <axes>

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        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
    </axes>
</placement>
<!-- Counterbore Hole Feature Definition -->
<counterbore_hole id="CBH2">
    <smaller_hole>
        <bottom_condition>
            <through_bottom_condition/>
        </bottom_condition>
        <diameter>
            <circular_closed_profile diameter="10"/>
        </diameter>
        <hole_depth distance="10">
            </hole_depth>
        </smaller_hole>
        <larger_hole>
            <change_in_diameter>
            </change_in_diameter>
            <bottom_condition>
            </bottom_condition>
            <diameter>
                <circular_closed_profile diameter="15"/>
            </diameter>
            <hole_depth distance="5">
            </hole_depth>
        </larger_hole>
    </counterbore_hole>
    <its_tolerance>
    </its_tolerance>
</its_feature>
<its_operation>
<!-- Counterboring Machining Operation -->
<counterboring its_id="CBH2-CB">
    <overcut_length>0.00</overcut_length>
    <cut_depth>8.00</cut_depth>
    <previous_diameter>10.00</previous_diameter>
    <dwel_time_bottom>5.00</dwel_time_bottom>
    <feed_on_retract>0.35</feed_on_retract>
    <its_machining_strategy>
        <reduced_cut_at_start>16.60</reduced_cut_at_start>
        <reduced_feed_at_start>0.29</reduced_feed_at_start>
        <depth_of_start>0.00</depth_of_start>
        <reduced_cut_at_end>16.60</reduced_cut_at_end>
        <reduced_feed_at_end>0.29</reduced_feed_at_end>
        <depth_of_end>0.00</depth_of_end>
    </its_machining_strategy>
    <!-- Counterbore Tool -->
    <its_tool>
        <counterbore its_id="CB-49">
            <overall_assembly_length>0.00</overall_assembly_length>
            <its_toolbody>

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<number_of_teeth>0</number_of_teeth>
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  <tool_length>0.00</tool_length>
  <flute_length>0.00</flute_length>
  <holder_diameter>0.00</holder_diameter>
  <holder_length>0.00</holder_length>
  <shank_diameter>0.00</shank_diameter>
  <tip_length>0.00</tip_length>
</dimension>
</its_toolbody>
<its_cutting_edge>
  <its_material>
    <material_id>HSS</material_id>
    <material_description></material_description>
    <material_hardness>
      <scale>BHN</scale>
      <high_value>550.00</high_value>
      <low_value>250.00</low_value>
      <nominal>350.00</nominal>
    </material_hardness>
  </its_material>
</its_cutting_edge>
</counterbore>
</its_tool>
<its_technology>
  <cutting_speed>19.53</cutting_speed>
  <feed_rate>0.345</feed_rate>
  <feed_speed>142.907</feed_speed>
  <spindle_speed>414</spindle_speed>
  <depth_of_cut>0.00</depth_of_cut>
  <passes>1</passes>
  <width_of_cut>0.00</width_of_cut>
  <machined_length>8.00</machined_length>
  <machined_diameter>15.00</machined_diameter>
  <machined_time>0.06</machined_time>
  <removal_rate>14,029.84</removal_rate>
  <power_at_spindle>0.84</power_at_spindle>
  <power_at_motor>1.05</power_at_motor>
  <torque_at_spindle>19.42</torque_at_spindle>
</its_technology>
<its_machine_functions>
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  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Light_Duty>
      <Soluble_Oil/>

```

```

        <Semichemical/>
        <Semisynthetic/>
    </Emulsifiable_Oils-Light_Duty>
    <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
    </Chemicals_and_Synthesis-Light_Duty>
</cutting_fluids>
<coolant_pressure>0</coolant_pressure>
<mist>False</mist>
<through_spindle_coolant>False</through_spindle_coolant>
<through_pressure>0.00</through_pressure>
<chip_removal>False</chip_removal>
</its_machine_functions>
</counterboring>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS6920</its_id>
    <its_feature>
        <usage_name></usage_name>
        <placement>
            <location x="185" y="61.25" z="35"/>
            <axes>
                <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
                <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
                <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
            </axes>
        </placement>
        <!-- Round Hole Feature Definition -->
        <round_hole id="RH1">
            <bottom_condition>
                <through_bottom_condition/>
            </bottom_condition>
            <diameter>
                <circular_closed_profile diameter="12"/>
            </diameter>
            <hole_depth distance="10">
            </hole_depth>
        </round_hole>
        <its_tolerance>
        <!-- Size Tolerance -->
        <diameter_dimension_tolerance>
            <dimension_value>12</dimension_value>
            <units_of_measure>micro meter</units_of_measure>
            <significant_digits>3</significant_digits>
            <dimension_description>Hole Diameter</dimension_description>
            <tolerance_value>
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                    <upper_limit>0.075</upper_limit>
                    <lower_limit>0</lower_limit>
                    <significant_digits>0</significant_digits>

```

```

        </plus_minus_value>
        </tolerance_value>
    </diameter_dimension_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- Reaming Machining Operation -->
<reaming its_id="RH1-R">
    <overcut_length>3.00</overcut_length>
    <cut_depth>13.00</cut_depth>
    <previous_diameter>11.00</previous_diameter>
    <dwelt_time_bottom>5.00</dwelt_time_bottom>
    <feed_on_retract>0.32</feed_on_retract>
    <its_machining_strategy>
        <reduced_cut_at_start>16.59</reduced_cut_at_start>
        <reduced_feed_at_start>0.27</reduced_feed_at_start>
        <depth_of_start>0.00</depth_of_start>
        <reduced_cut_at_end>16.59</reduced_cut_at_end>
        <reduced_feed_at_end>0.27</reduced_feed_at_end>
        <depth_of_end>0.00</depth_of_end>
    </its_machining_strategy>
    <!-- Reamer Tool -->
    <its_tool>
        <reamer its_id="RM-37">
            <overall_assembly_length>0.00</overall_assembly_length>
            <its_toolbody>
                <number_of_teeth>0</number_of_teeth>
                <coolant_through_tool>False</coolant_through_tool>
                <dimension>
                    <diameter>12.00</diameter>
                    <tool_length>0.00</tool_length>
                    <flute_length>76.00</flute_length>
                    <holder_diameter>0.00</holder_diameter>
                    <holder_length>0.00</holder_length>
                    <primary_relief_angle>0.00</primary_relief_angle>
                    <secondary_relief_angle>0.00</secondary_relief_angle>
                    <margin_width>0.00</margin_width>
                    <chamfer_angle>0.00</chamfer_angle>
                    <primary_chamfer_angle>0.00</primary_chamfer_angle>
                    <secondary_chamfer_angle>0.00</secondary_chamfer_angle>
                    <chamfer_length>0.00</chamfer_length>
                    <helix_angle>0.00</helix_angle>
                    <flutes>0</flutes>
                </dimension>
            </its_toolbody>
            <its_cutting_edge>
                <its_material>
                    <material_id></material_id>
                    <material_description></material_description>
                    <material_hardness>
                        <scale></scale>
                        <high_value>0.00</high_value>
                        <low_value>0.00</low_value>
                    </material_hardness>
                </its_material>
            </its_cutting_edge>
        </reamer its_id="RM-37">
    </its_tool>
</!-- Reamer Tool -->
</its_operation>
</its_feature>

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```

        <nominal>0.00</nominal>
    </material_hardness>
</its_material>
    </its_cutting_edge>
</reamer>
</its_tool>
<its_technology>
    <cutting_speed>19.52</cutting_speed>
    <feed_rate>0.316</feed_rate>
    <feed_speed>163.458</feed_speed>
    <spindle_speed>518</spindle_speed>
    <depth_of_cut>0.50</depth_of_cut>
    <passes>1</passes>
    <width_of_cut>0.00</width_of_cut>
    <machined_length>16.00</machined_length>
    <machined_diameter>12.00</machined_diameter>
    <machined_time>0.10</machined_time>
    <removal_rate>2,952.73</removal_rate>
    <power_at_spindle>0.18</power_at_spindle>
    <power_at_motor>0.22</power_at_motor>
    <torque_at_spindle>3.27</torque_at_spindle>
</its_technology>
<its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
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            <Straight_Mineral_Oil/>
            <Straight_Fatty_Oil/>
            <Mineral_Oil_and_Fatty_Oil/>
            <Mineral_Oil_and_Additives/>
        </Oils-Light_Duty>
        <Emulsifiable_Oils-Light_Duty>
            <Soluble_Oil/>
            <Semichemical/>
            <Semisynthetic/>
        </Emulsifiable_Oils-Light_Duty>
        <Chemicals_and_Synthesis-Light_Duty>
            <Solutions/>
            <Synthetic_Emulsions/>
        </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
</its_machine_functions>
</reaming>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS61021</its_id>

```

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<its_feature>
  <usage_name></usage_name>
  <placement>
    <location x="185" y="113.75" z="35"/>
    <axes>
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      <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
      <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
    </axes>
  </placement>
  <!-- Round Hole Feature Definition -->
  <round_hole id="RH2">
    <bottom_condition>
      <through_bottom_condition/>
    </bottom_condition>
    <diameter>
      <circular_closed_profile diameter="12"/>
    </diameter>
    <hole_depth distance="10">
    </hole_depth>
  </round_hole>
  <its_tolerance>
  <!-- Size Tolerance -->
  <diameter_dimension_tolerance>
    <dimension_value>12</dimension_value>
    <units_of_measure>micro meter</units_of_measure>
    <significant_digits>3</significant_digits>
    <dimension_description>Hole Diameter</dimension_description>
    <tolerance_value>
      <plus_minus_value>
        <upper_limit>0.075</upper_limit>
        <lower_limit>0</lower_limit>
        <significant_digits>0</significant_digits>
      </plus_minus_value>
    </tolerance_value>
  </diameter_dimension_tolerance>
  </its_tolerance>
</its_feature>
<its_operation>
<!-- Reaming Machining Operation -->
<reaming its_id="RH2-R">
  <overcut_length>3.00</overcut_length>
  <cut_depth>13.00</cut_depth>
  <previous_diameter>11.00</previous_diameter>
  <dwelling_time_bottom>5.00</dwelling_time_bottom>
  <feed_on_retract>0.32</feed_on_retract>
  <its_machining_strategy>
    <reduced_cut_at_start>16.59</reduced_cut_at_start>
    <reduced_feed_at_start>0.27</reduced_feed_at_start>
    <depth_of_start>0.00</depth_of_start>
    <reduced_cut_at_end>16.59</reduced_cut_at_end>
    <reduced_feed_at_end>0.27</reduced_feed_at_end>
    <depth_of_end>0.00</depth_of_end>
  </its_machining_strategy>
</reaming>
</its_operation>

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```

</its_machining_strategy>
<!-- Reamer Tool -->
<its_tool>
  <reamer its_id="RM-37">
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    <its_toolbody>
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      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
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        <flute_length>76.00</flute_length>
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        <holder_length>0.00</holder_length>
        <primary_relief_angle>0.00</primary_relief_angle>
        <secondary_relief_angle>0.00</secondary_relief_angle>
        <margin_width>0.00</margin_width>
        <chamfer_angle>0.00</chamfer_angle>
        <primary_chamfer_angle>0.00</primary_chamfer_angle>
        <secondary_chamfer_angle>0.00</secondary_chamfer_angle>
        <chamfer_length>0.00</chamfer_length>
        <helix_angle>0.00</helix_angle>
        <flutes>0</flutes>
      </dimension>
    </its_toolbody>
    <its_cutting_edge>
      <its_material>
        <material_id></material_id>
        <material_description></material_description>
        <material_hardness>
          <scale></scale>
          <high_value>0.00</high_value>
          <low_value>0.00</low_value>
          <nominal>0.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </reamer>
</its_tool>
<its_technology>
  <cutting_speed>19.52</cutting_speed>
  <feed_rate>0.316</feed_rate>
  <feed_speed>163.458</feed_speed>
  <spindle_speed>518</spindle_speed>
  <depth_of_cut>0.50</depth_of_cut>
  <passes>1</passes>
  <width_of_cut>0.00</width_of_cut>
  <machined_length>16.00</machined_length>
  <machined_diameter>12.00</machined_diameter>
  <machined_time>0.10</machined_time>
  <removal_rate>2,952.73</removal_rate>
  <power_at_spindle>0.18</power_at_spindle>
  <power_at_motor>0.22</power_at_motor>

```

```

    <torque_at_spindle>3.27</torque_at_spindle>
  </its_technology>
  <its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
      <Oils-Light_Duty>
        <Straight_Mineral_Oil/>
        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Light_Duty>
        <Soluble_Oil/>
        <Semichemical/>
        <Semisynthetic/>
      </Emulsifiable_Oils-Light_Duty>
      <Chemicals_and_Synthesis-Light_Duty>
        <Solutions/>
        <Synthetic_Emulsions/>
      </Chemicals_and_Synthesis-Light_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
  </its_machine_functions>
</reaming>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS6522</its_id>
  <its_feature>
    <usage_name>Fixing</usage_name>
    <placement>
      <location x="65" y="87.5" z="35"/>
      <axes>
        <x_axis x_direction_ratio="0" y_direction_ratio="-1" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
        <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
      </axes>
    </placement>
    <!-- Square Slot Feature Definition -->
    <slot id="SQ1">
      <end_condition>
        <first_end_condition>
          <radiused_slot_end_type/>
        </first_end_condition>
        <second_end_condition>
          <radiused_slot_end_type/>
        </second_end_condition>
      </end_condition>
    </slot>
  </its_feature>
</machining_workingstep>

```

```

<course_of_travel distance="30">
</course_of_travel>
<square_u_profile>
  <first_angle>0</first_angle>
  <first_radius>0</first_radius>
  <second_angle>0</second_angle>
  <second_radius>0</second_radius>
  <width>12</width>
  <depth>10</depth>
</square_u_profile>
</slot>
<its_tolerance>
<!-- Size Tolerance -->
<curved_dimension_tolerance>
  <dimension_value>6</dimension_value>
  <units_of_measure>milli meter</units_of_measure>
  <significant_digits>3</significant_digits>
  <dimension_description>Slot Radius</dimension_description>
  <tolerance_value>
    <plus_minus_value>
      <upper_limit>0.1</upper_limit>
      <lower_limit>0</lower_limit>
      <significant_digits>0</significant_digits>
    </plus_minus_value>
  </tolerance_value>
</curved_dimension_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_finish_milling its_id="SQ1-BSFM-F">
  <overcut_length>0.00</overcut_length>
  <axial_cutting_depth>1.00</axial_cutting_depth>
  <radial_cutting_depth>2.00</radial_cutting_depth>
  <allowance_side>1.00</allowance_side>
  <allowance_bottom>1.00</allowance_bottom>
  <its_machining_strategy>
    <overlap>0.00</overlap>
    <allow_multiple_passes>True</allow_multiple_passes>
    <unidirectional>
      <feed_direction>
        <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
      </feed_direction>
      <cutmode>0</cutmode>
    </unidirectional>
  </its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
  <endmill its_id="SEM-10">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>3</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
    </its_toolbody>
  </endmill>
</its_tool>

```

```

    <dimension>
      <diameter>12.00</diameter>
      <tool_length>83.00</tool_length>
      <flute_length>26.00</flute_length>
      <holder_diameter>0.00</holder_diameter>
      <holder_length>0.00</holder_length>
      <helix_angle>32.09</helix_angle>
      <radial_rake>8.04</radial_rake>
      <radial_relief>10.42</radial_relief>
      <radial_clearance>15.37</radial_clearance>
      <cutting_edge_angle>0.99</cutting_edge_angle>
      <end_relief>6.00</end_relief>
    </dimension>
  </its_toolbody>
  <its_cutting_edge>
    <its_material>
      <material_id>HSS</material_id>
      <material_description></material_description>
      <material_hardness>
        <scale>BHN</scale>
        <high_value>550.00</high_value>
        <low_value>250.00</low_value>
        <nominal>350.00</nominal>
      </material_hardness>
    </its_material>
  </its_cutting_edge>
</endmill>
</its_tool>
<its_technology>
  <cutting_speed>19.56</cutting_speed>
  <feed_rate>0.000</feed_rate>
  <feed_speed>75.154</feed_speed>
  <spindle_speed>519</spindle_speed>
  <total_depth_of_cut>1.00</total_depth_of_cut>
  <depth_of_cut>1.00</depth_of_cut>
  <passes>1</passes>
  <total_width_of_cut>2.00</total_width_of_cut>
  <width_of_cut>2.00</width_of_cut>
  <loops>1</loops>
  <machined_length>18.00</machined_length>
  <machined_time>0.24</machined_time>
  <removal_rate>150.31</removal_rate>
  <power_at_spindle>0.01</power_at_spindle>
  <power_at_motor>0.01</power_at_motor>
  <torque_at_spindle>0.17</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
    </Oils-Light_Duty>
  </cutting_fluids>
</its_machine_functions>

```

```

        <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Heavy_Duty>
        <Sulfurized_Fatty_Soluble_Oil/>
        <Chlorinated_Soluble_Oil/>
    </Emulsifiable_Oils-Heavy_Duty>
</cutting_fluids>
<coolant_pressure>0</coolant_pressure>
<mist>False</mist>
<through_spindle_coolant>False</through_spindle_coolant>
<through_pressure>0.00</through_pressure>
<chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_finish_milling>
</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
    <its_id> WS6823</its_id>
    <its_feature>
        <usage_name>Fixing</usage_name>
        <placement>
            <location x="185" y="87.5" z="35"/>
            <axes>
                <x_axis x_direction_ratio="0" y_direction_ratio="-1" z_direction_ratio="0"/>
                <y_axis x_direction_ratio="-1" y_direction_ratio="0" z_direction_ratio="0"/>
                <z_axis x_direction_ratio="0" y_direction_ratio="0" z_direction_ratio="1"/>
            </axes>
        </placement>
        <!-- Square Slot Feature Definition -->
        <slot id="SQ4">
            <end_condition>
                <first_end_condition>
                    <radiused_slot_end_type/>
                </first_end_condition>
                <second_end_condition>
                    <radiused_slot_end_type/>
                </second_end_condition>
            </end_condition>
            <course_of_travel distance="30">
        </course_of_travel>
            <square_u_profile>
                <first_angle>0</first_angle>
                <first_radius>0</first_radius>
                <second_angle>0</second_angle>
                <second_radius>0</second_radius>
                <width>12</width>
                <depth>10</depth>
            </square_u_profile>
        </slot>
        <its_tolerance>
        <!-- Size Tolerance -->
        <curved_dimension_tolerance>

```

```

    <dimension_value>6</dimension_value>
    <units_of_measure>milli meter</units_of_measure>
    <significant_digits>3</significant_digits>
    <dimension_description>Slot Radius</dimension_description>
    <tolerance_value>
      <plus_minus_value>
        <upper_limit>0.1</upper_limit>
        <lower_limit>0</lower_limit>
        <significant_digits>0</significant_digits>
      </plus_minus_value>
    </tolerance_value>
  </curved_dimension_tolerance>
</its_tolerance>
</its_feature>
<its_operation>
<!-- End milling Machining Operation -->
<bottom_side_finish_milling its_id="SQ4-BSFM-F">
  <overcut_length>0.00</overcut_length>
  <axial_cutting_depth>1.00</axial_cutting_depth>
  <radial_cutting_depth>2.00</radial_cutting_depth>
  <allowance_side>1.00</allowance_side>
  <allowance_bottom>1.00</allowance_bottom>
  <its_machining_strategy>
    <overlap>0.00</overlap>
    <allow_multiple_passes>True</allow_multiple_passes>
    <unidirectional>
      <feed_direction>
        <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>
      </feed_direction>
      <cutmode>0</cutmode>
    </unidirectional>
  </its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
  <endmill its_id="SEM-10">
    <overall_assembly_length>0</overall_assembly_length>
    <its_toolbody>
      <number_of_teeth>3</number_of_teeth>
      <coolant_through_tool>False</coolant_through_tool>
      <dimension>
        <diameter>12.00</diameter>
        <tool_length>83.00</tool_length>
        <flute_length>26.00</flute_length>
        <holder_diameter>0.00</holder_diameter>
        <holder_length>0.00</holder_length>
        <helix_angle>32.09</helix_angle>
        <radial_rake>8.04</radial_rake>
        <radial_relief>10.42</radial_relief>
        <radial_clearance>15.37</radial_clearance>
        <cutting_edge_angle>0.99</cutting_edge_angle>
        <end_relief>6.00</end_relief>
      </dimension>
    </its_toolbody>
  </endmill>
</its_tool>

```

```

    <its_cutting_edge>
      <its_material>
        <material_id>HSS</material_id>
        <material_description></material_description>
        <material_hardness>
          <scale>BHN</scale>
          <high_value>550.00</high_value>
          <low_value>250.00</low_value>
          <nominal>350.00</nominal>
        </material_hardness>
      </its_material>
    </its_cutting_edge>
  </endmill>
</its_tool>
<its_technology>
  <cutting_speed>19.56</cutting_speed>
  <feed_rate>0.000</feed_rate>
  <feed_speed>75.154</feed_speed>
  <spindle_speed>519</spindle_speed>
  <total_depth_of_cut>1.00</total_depth_of_cut>
  <depth_of_cut>1.00</depth_of_cut>
  <passes>1</passes>
  <total_width_of_cut>2.00</total_width_of_cut>
  <width_of_cut>2.00</width_of_cut>
  <loops>1</loops>
  <machined_length>18.00</machined_length>
  <machined_time>0.24</machined_time>
  <removal_rate>150.31</removal_rate>
  <power_at_spindle>0.01</power_at_spindle>
  <power_at_motor>0.01</power_at_motor>
  <torque_at_spindle>0.17</torque_at_spindle>
</its_technology>
<its_machine_functions>
  <coolant>True</coolant>
  <cutting_fluids>
    <Oils-Light_Duty>
      <Straight_Mineral_Oil/>
      <Straight_Fatty_Oil/>
      <Mineral_Oil_and_Fatty_Oil/>
      <Mineral_Oil_and_Additives/>
    </Oils-Light_Duty>
    <Emulsifiable_Oils-Heavy_Duty>
      <Sulfurized_Fatty_Soluble_Oil/>
      <Chlorinated_Soluble_Oil/>
    </Emulsifiable_Oils-Heavy_Duty>
  </cutting_fluids>
  <coolant_pressure>0</coolant_pressure>
  <mist>False</mist>
  <through_spindle_coolant>False</through_spindle_coolant>
  <through_pressure>0.00</through_pressure>
  <chip_removal>False</chip_removal>
</its_machine_functions>
</bottom_side_finish_milling>

```

```

</its_operation>
</machining_workingstep>
<!-- Machining Working Step-->
<machining_workingstep>
  <its_id> WS61324</its_id>
  <its_feature>
    <usage_name></usage_name>
    <placement>
      <location x="125" y="87.5" z="55"/>
      <axes>
        <x_axis x_direction_ratio="1" y_direction_ratio="0" z_direction_ratio="0"/>
        <y_axis x_direction_ratio="0" y_direction_ratio="1" z_direction_ratio="0"/>
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      </axes>
    </placement>
    <!-- Square Slot Feature Definition -->
    <slot id="SQ5">
      <end_condition>
        <first_end_condition>
          <open_slot_end_type/>
        </first_end_condition>
        <second_end_condition>
          <open_slot_end_type/>
        </second_end_condition>
      </end_condition>
      <course_of_travel distance="90">
    </course_of_travel>
      <square_u_profile>
        <first_angle>0</first_angle>
        <first_radius>0</first_radius>
        <second_angle>0</second_angle>
        <second_radius>0</second_radius>
        <width>10</width>
        <depth>10</depth>
      </square_u_profile>
    </slot>
    <its_tolerance>
    </its_tolerance>
  </its_feature>
  <its_operation>
  <!-- End milling Machining Operation -->
  <bottom_side_finish_milling its_id="SQ5-BSFM-F">
    <overcut_length>5.00</overcut_length>
    <axial_cutting_depth>1.00</axial_cutting_depth>
    <radial_cutting_depth>2.00</radial_cutting_depth>
    <allowance_side>1.00</allowance_side>
    <allowance_bottom>1.00</allowance_bottom>
    <its_machining_strategy>
      <overlap>0.00</overlap>
      <allow_multiple_passes>True</allow_multiple_passes>
      <unidirectional>
        <feed_direction>
          <direction x_ratio="0.00" y_ratio="0.00" z_ratio="0.00"/>

```



```

        </feed_direction>
        <cutmode>0</cutmode>
    </unidirectional>
</its_machining_strategy>
<!-- End Mill Cutter -->
<its_tool>
    <endmill its_id="SEM-9">
        <overall_assembly_length>0</overall_assembly_length>
        <its_toolbody>
            <number_of_teeth>3</number_of_teeth>
            <coolant_through_tool>False</coolant_through_tool>
            <dimension>
                <diameter>10.00</diameter>
                <tool_length>72.00</tool_length>
                <flute_length>22.00</flute_length>
                <holder_diameter>0.00</holder_diameter>
                <holder_length>0.00</holder_length>
                <helix_angle>32.09</helix_angle>
                <radial_rake>8.04</radial_rake>
                <radial_relief>10.42</radial_relief>
                <radial_clearance>15.37</radial_clearance>
                <cutting_edge_angle>0.99</cutting_edge_angle>
                <end_relief>6.00</end_relief>
            </dimension>
        </its_toolbody>
        <its_cutting_edge>
            <its_material>
                <material_id>HSS</material_id>
                <material_description></material_description>
                <material_hardness>
                    <scale>BHN</scale>
                    <high_value>550.00</high_value>
                    <low_value>250.00</low_value>
                    <nominal>350.00</nominal>
                </material_hardness>
            </its_material>
        </its_cutting_edge>
    </endmill>
</its_tool>
<its_technology>
    <cutting_speed>19.56</cutting_speed>
    <feed_rate>0.000</feed_rate>
    <feed_speed>90.214</feed_speed>
    <spindle_speed>623</spindle_speed>
    <total_depth_of_cut>1.00</total_depth_of_cut>
    <depth_of_cut>1.00</depth_of_cut>
    <passes>1</passes>
    <total_width_of_cut>2.00</total_width_of_cut>
    <width_of_cut>2.00</width_of_cut>
    <loops>1</loops>
    <machined_length>100.00</machined_length>
    <machined_time>1.11</machined_time>
    <removal_rate>180.43</removal_rate>

```

```

    <power_at_spindle>0.01</power_at_spindle>
    <power_at_motor>0.01</power_at_motor>
    <torque_at_spindle>0.17</torque_at_spindle>
  </its_technology>
  <its_machine_functions>
    <coolant>True</coolant>
    <cutting_fluids>
      <Oils-Light_Duty>
        <Straight_Mineral_Oil/>
        <Straight_Fatty_Oil/>
        <Mineral_Oil_and_Fatty_Oil/>
        <Mineral_Oil_and_Additives/>
      </Oils-Light_Duty>
      <Emulsifiable_Oils-Heavy_Duty>
        <Sulfurized_Fatty_Soluble_Oil/>
        <Chlorinated_Soluble_Oil/>
      </Emulsifiable_Oils-Heavy_Duty>
    </cutting_fluids>
    <coolant_pressure>0</coolant_pressure>
    <mist>False</mist>
    <through_spindle_coolant>False</through_spindle_coolant>
    <through_pressure>0.00</through_pressure>
    <chip_removal>False</chip_removal>
  </its_machine_functions>
</bottom_side_finish_milling>
</its_operation>
</machining_workingstep>
</its_elements>
</main_workplan>
</its_workpiece>
</project>
</STEP-XML>

```

APPENDIX D

STEP-FM FEATURES LIBRARY

Table D.1 STEP Features Library

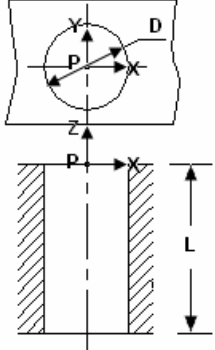
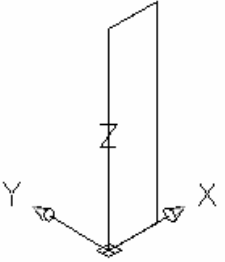

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
<p style="text-align: center;">Round hole with trough bottom</p>				<p>D = hole diameter L = hole depth $P(x,y,z)$ = location point</p>

Table D.1 (Continued) STEP Features Library

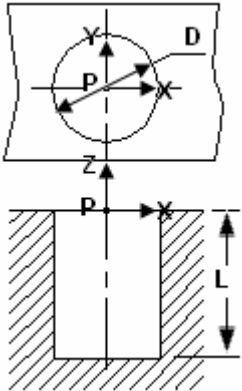
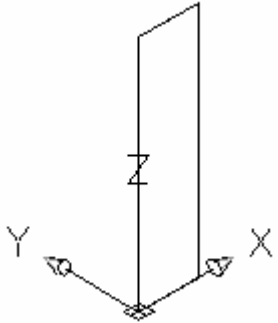

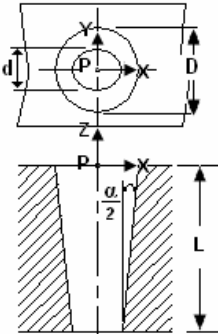
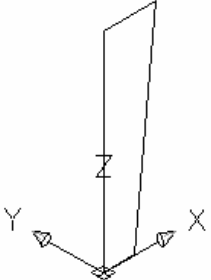
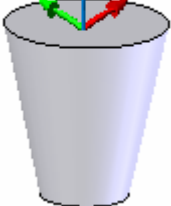
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Round hole with blind bottom				<p>D = hole diameter L = hole depth P(x,y,z) = location point</p>
Tapered Round hole with through bottom				<p>D = Large hole diameter d = Small hole diameter L = hole depth α = taper angle P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Tapered Round hole with blind bottom				<p> D = Large hole diameter d = Small hole diameter L = hole depth α = taper angle $P(x,y,z)$ = location point </p>
Round blind hole with conical bottom				<p> D = hole diameter R = Tip radius L = Hole depth α = Conical angle $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

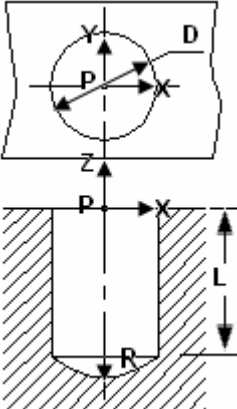
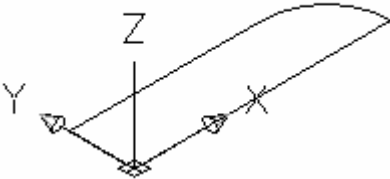

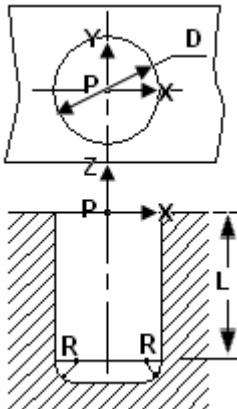
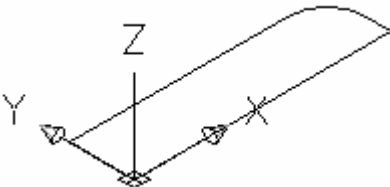

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Round blind hole with spherical bottom				<p>D = Hole diameter R = Radius L = Hole depth $P(x,y,z)$ = location point</p>
Round blind hole with radiused bottom				<p>D = Hole diameter R = Corner radius L = Hole depth $P(x,y,z)$ = location point</p>

Table D.1 (Continued) STEP Features Library

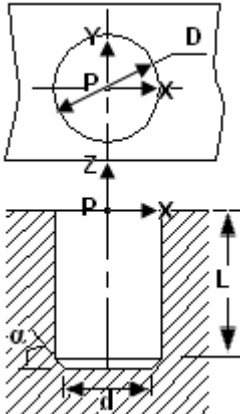
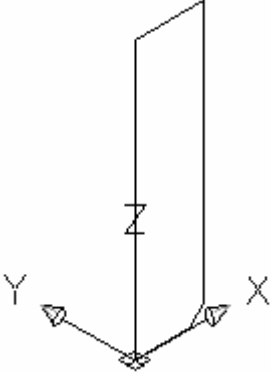

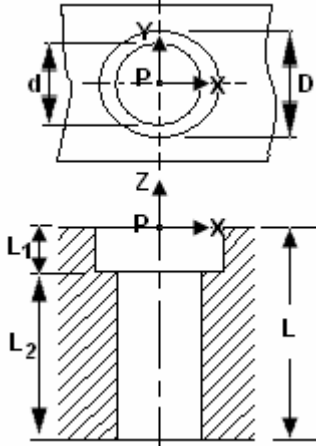
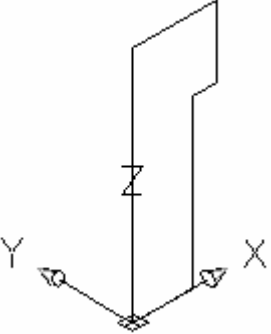
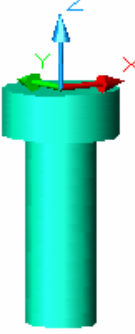
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Round blind hole with tapered bottom				<p> D = Hole diameter d = Final diameter L = hole depth α = taper angle $P(x,y,z)$ = location point </p>
Counterbore through hole				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

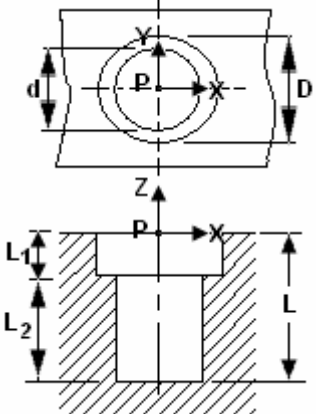
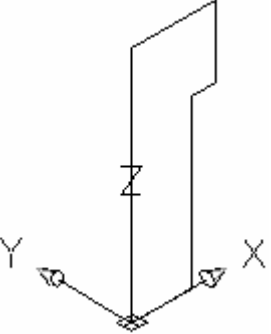
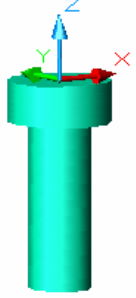
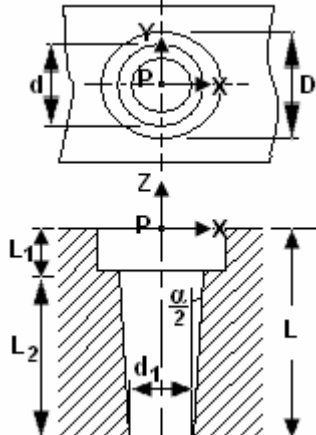
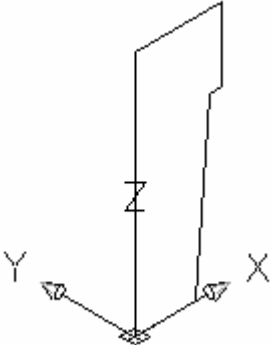

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Counterbore blind hole				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth $P(x,y,z)$ = location point </p>
Tapered counterbore hole with through bottom				<p> D = large hole diameter. d_1 = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Tapered counterbore blind hole				<p> D = large hole diameter. d_1 = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle $P(x,y,z)$ = location point </p>
Counterbore blind hole with conical bottom				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = conical angle $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

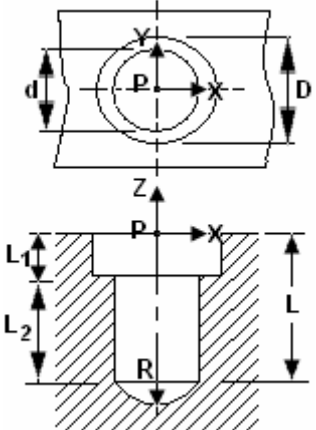
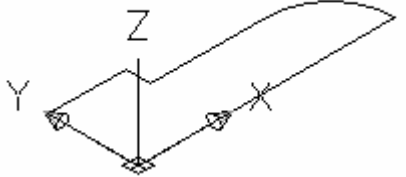

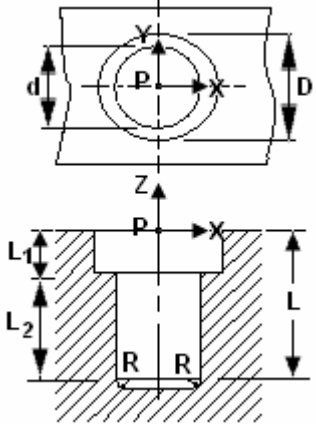
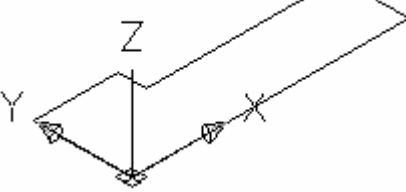

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Counterbore blind hole with spherical bottom				<p>D = large hole diameter. d = small hole diameter. L₁ = large hole depth L₂ = small hole depth L = hole depth R = spherical radius P(x,y,z) = location point</p>
Counterbore blind hole with radiused bottom				<p>D = large hole diameter. d = small hole diameter. L₁ = large hole depth L₂ = small hole depth L = hole depth R = corner radius P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

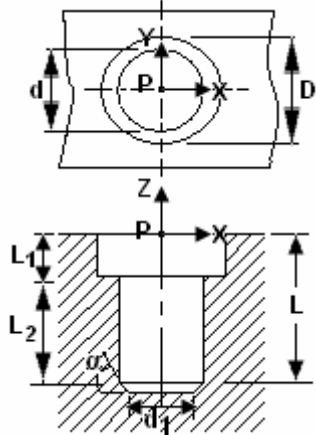
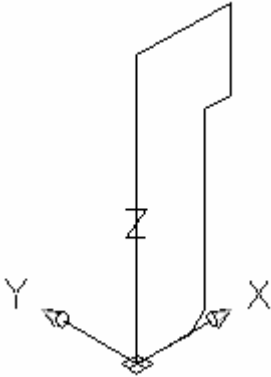

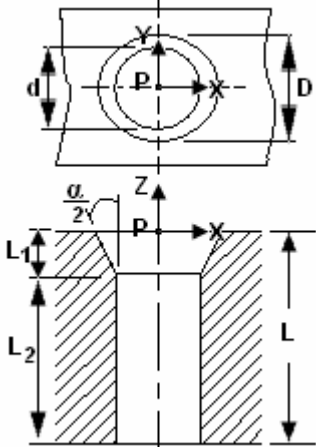
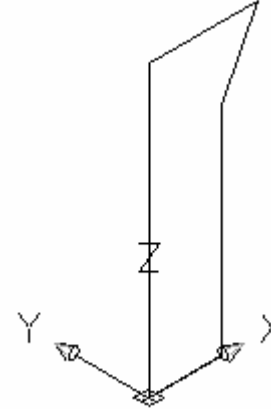
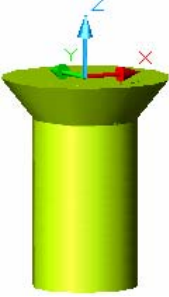
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Counterbore blind hole with tapered bottom				<p> D = large hole diameter. d = small hole diameter. d_1 = final hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle $P(x,y,z)$ = location point </p>
Countersunk hole with through bottom				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Countersunk hole with blind bottom				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle $P(x,y,z)$ = location point </p>
Countersunk blind hole with conical bottom				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = conical angle β = taper angle $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Countersunk blind hole with spherical bottom				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle R = spherical radius $P(x,y,z)$ = location point </p>
Countersunk blind hole with radiused bottom				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle R = corner radius $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Countersunk blind hole with tapered bottom				<p> D = large hole diameter. d = small hole diameter. L_1 = large hole depth L_2 = small hole depth L = hole depth α = taper angle β = bottom taper angle d_1 = final hole diameter $P(x,y,z)$ = location point </p>
Rectangular closed pocket				<p> L = pocket length W = pocket width h = pocket height $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

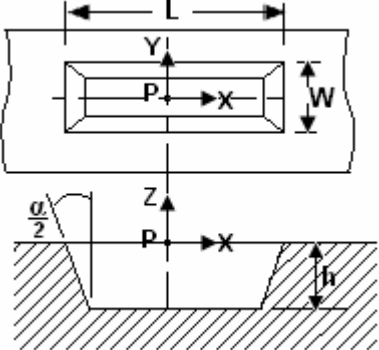
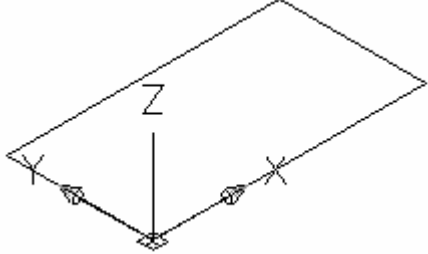
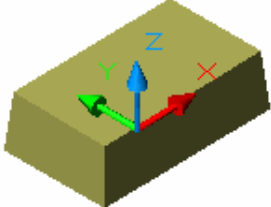
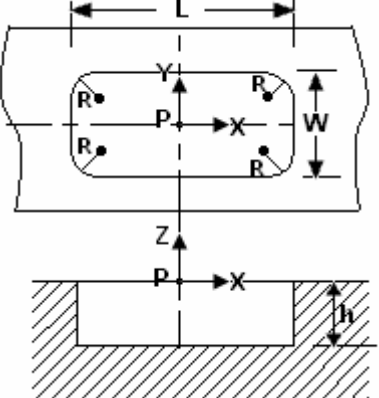
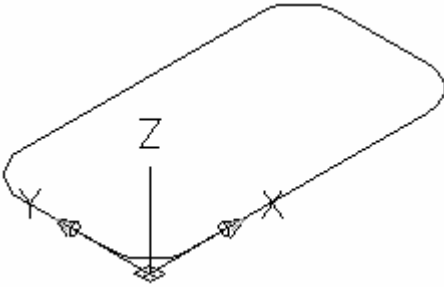
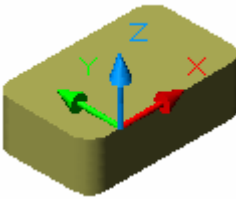
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Rectangular closed pocket With taper				L = pocket length W = pocket width h = pocket height α = taper angle P(x,y,z) = location point
Rectangular closed pocket with round corners				L = pocket length W = pocket width h = pocket height R = corner radius P(x,y,z) = location point

Table D.1 (Continued) STEP Features Library

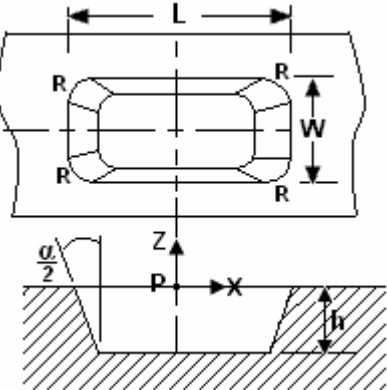
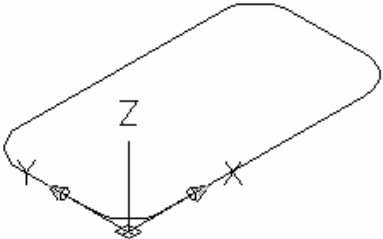
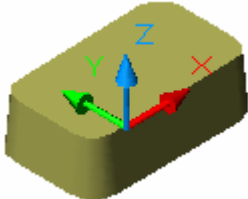
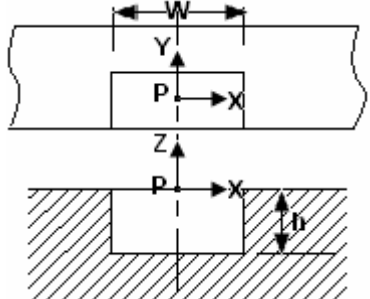
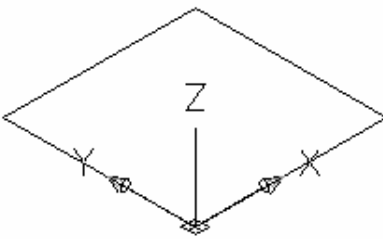
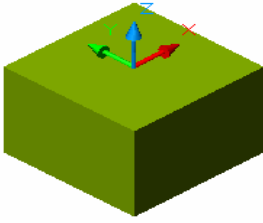
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Rectangular closed pocket with taper and round corners				<p>L = pocket length W = pocket width h = pocket height α = taper angle P(x,y,z) = location point</p>
Rectangular open pocket				<p>L = pocket length W = pocket width h = pocket height P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

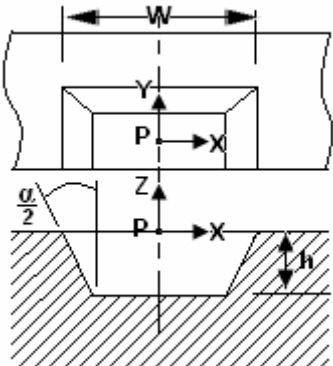
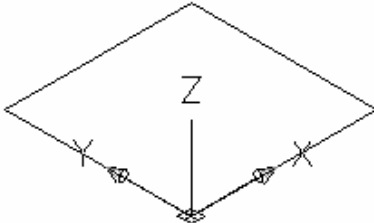
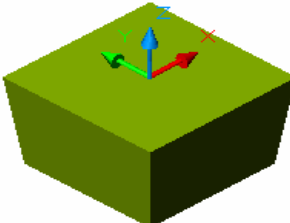
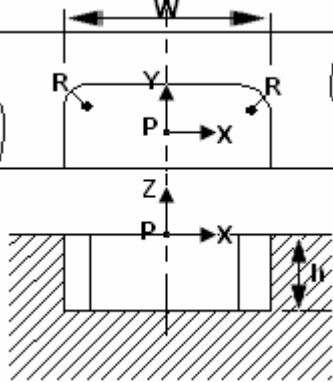
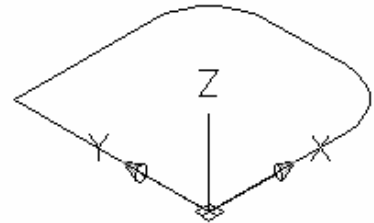
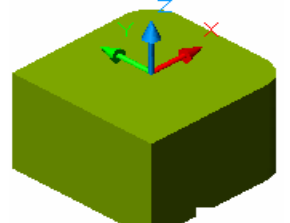
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Rectangular open pocket with taper				<p>L = pocket length W = pocket width h = pocket height α = taper angle P(x,y,z) = location point</p>
Rectangular open pocket with round corners				<p>L = pocket length W = pocket width h = pocket height R = corner radius P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

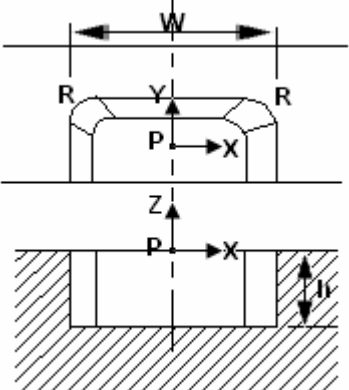
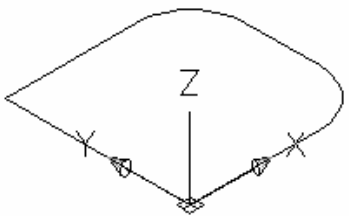
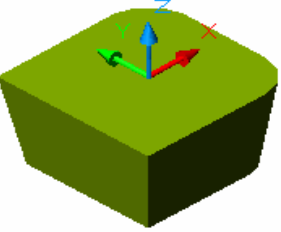
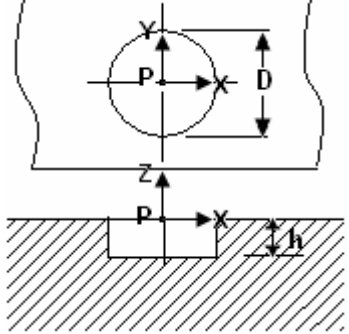
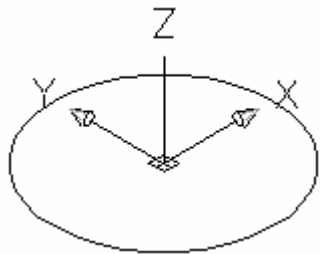
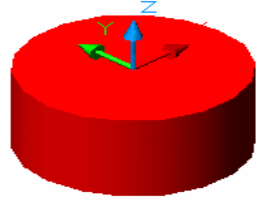
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Rectangular open pocket with taper and round corners				L = pocket length W = pocket width h = pocket height R = corner radius α = taper angle P(x,y,z) = location point
Circular pocket				D = pocket diameter h = pocket height P(x,y,z) = location point

Table D.1 (Continued) STEP Features Library

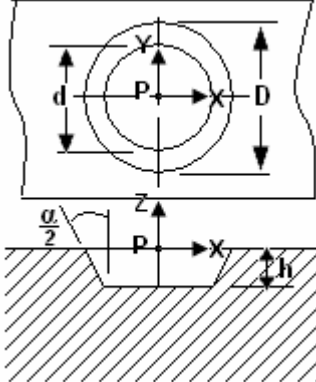
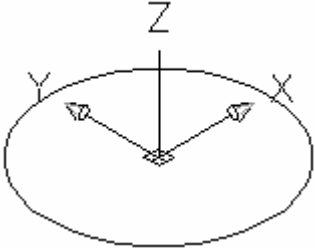
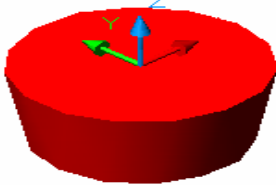
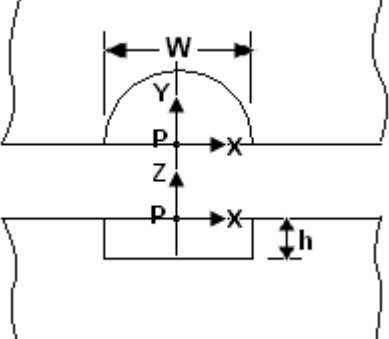
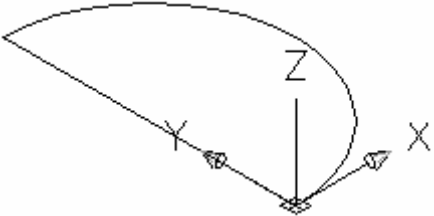
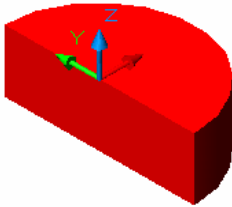
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Circular pocket with taper	 <p>The feature model shows a circular pocket with a tapered bottom. The top view shows a diameter d and a larger diameter D at the bottom. A location point P is marked at the center. The side view shows a taper angle $\frac{\alpha}{2}$ and a pocket height h. A 3D coordinate system with X, Y, and Z axes is centered at P.</p>	 <p>The 2D feature region is a circular arc representing the top surface of the pocket, with a vertical Z-axis and X, Y axes.</p>	 <p>The 3D feature volume is a red, tapered cylindrical shape representing the pocket.</p>	<p>D = pocket diameter h = pocket height α = taper angle $P(x,y,z)$ = location point</p>
Round pocket	 <p>The feature model shows a round pocket with a flat bottom. The top view shows a width W and a location point P at the center. The side view shows a pocket height h. A 3D coordinate system with X, Y, and Z axes is centered at P.</p>	 <p>The 2D feature region is a semi-circular arc representing the top surface of the pocket, with a vertical Z-axis and X, Y axes.</p>	 <p>The 3D feature volume is a red, semi-cylindrical shape representing the pocket.</p>	<p>W = pocket width h = pocket height $P(x,y,z)$ = location point</p>

Table D.1 (Continued) STEP Features Library

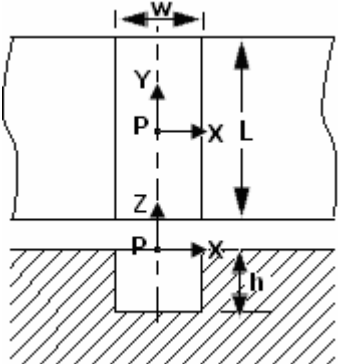
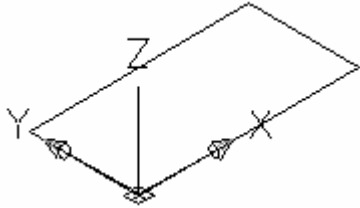
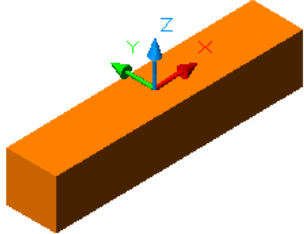
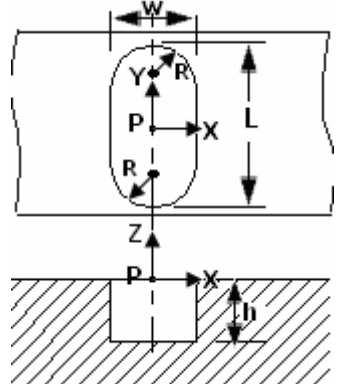
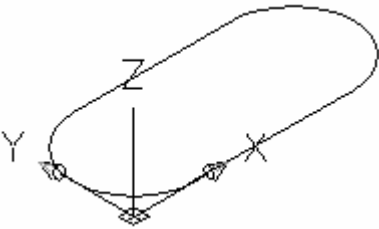
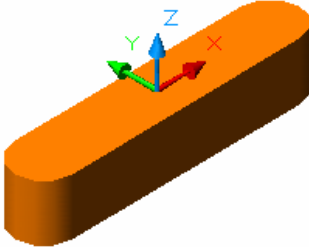
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Square slot with open ends				<p>W = slot width L = slot length h = slot depth P(x,y,z) = location point</p>
Square slot with radiused ends				<p>W = slot width L = slot length h = slot depth R = slot end radius P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Square slot with radiused end				<p>W = slot width L = slot length h = slot depth R = slot end radius P(x,y,z) = location point</p>
Square slot with woodruff end				<p>W = slot width L = slot length h = slot depth R = woodruff radius P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

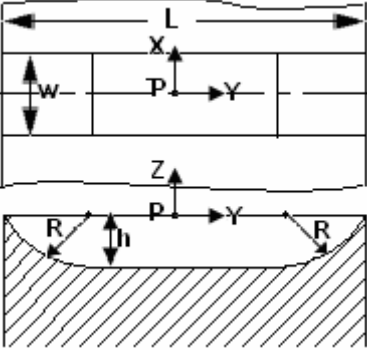
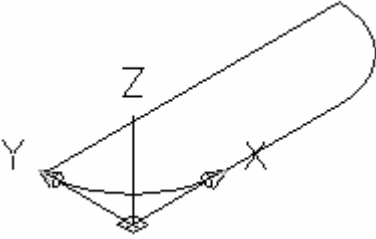
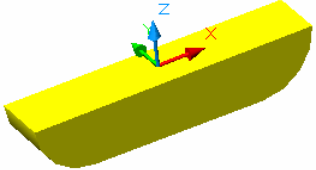
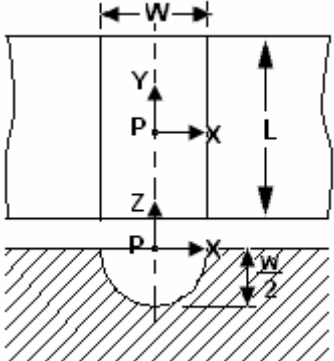
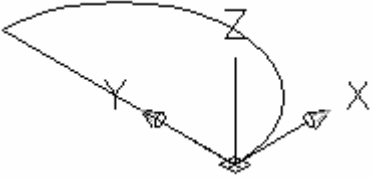
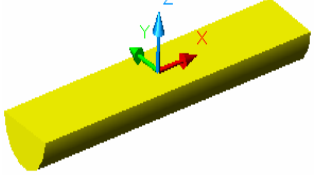
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Square slot with woodruff ends				<p>W = slot width L = slot length h = slot depth R = woodruff radius P(x,y,z) = location point</p>
Round slot				<p>W = slot width L = slot length P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

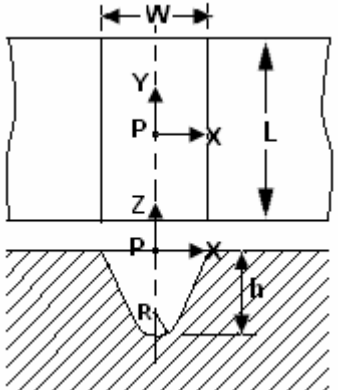
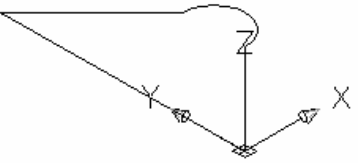
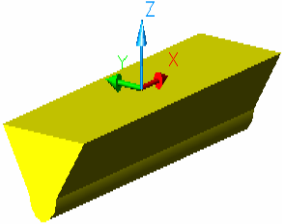
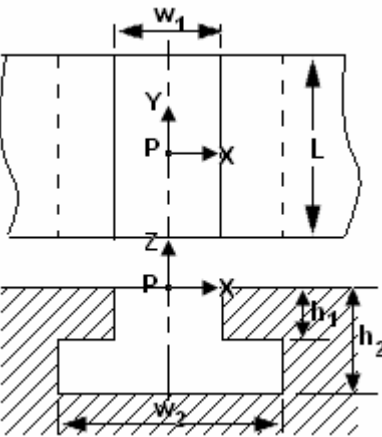
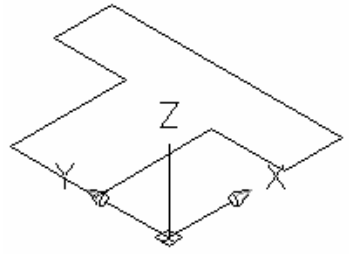
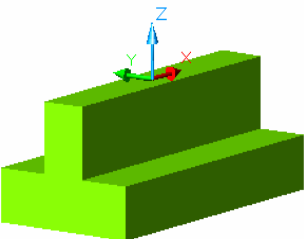
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Vee slot	 <p>The feature model for a Vee slot consists of two views. The top view shows a rectangular slot with width W and length L. A coordinate system is centered at the slot, with the Z-axis pointing downwards. The location point P is marked at the center. The side view shows a V-shaped cutout with a height h and a radius R at the bottom. The Z-axis is vertical, and the X-axis is horizontal.</p>	 <p>The 2D feature region is a triangular shape with a curved bottom edge, representing the cross-section of the Vee slot. It is oriented with the vertex at the bottom and the base at the top. A coordinate system is shown with the Z-axis pointing downwards and the X-axis pointing to the right.</p>	 <p>The 3D feature volume is a yellow rectangular block with a V-shaped cutout. A coordinate system is shown with the Z-axis pointing upwards, the X-axis pointing to the right, and the Y-axis pointing out of the page.</p>	<p> W = slot width L = slot length R = Radius h = slot height $P(x,y,z)$ = location point </p>
Tee slot	 <p>The feature model for a Tee slot consists of two views. The top view shows a T-shaped slot with a stem width W_1 and a cross bar width W_2. The length of the slot is L. A coordinate system is centered at the stem, with the Z-axis pointing downwards. The location point P is marked at the center. The side view shows a T-shaped cutout with a stem height h_1 and a cross bar height h_2. The Z-axis is vertical, and the X-axis is horizontal.</p>	 <p>The 2D feature region is a T-shaped region representing the cross-section of the Tee slot. It is oriented with the stem at the top and the cross bar at the bottom. A coordinate system is shown with the Z-axis pointing downwards and the X-axis pointing to the right.</p>	 <p>The 3D feature volume is a green rectangular block with a T-shaped cutout. A coordinate system is shown with the Z-axis pointing upwards, the X-axis pointing to the right, and the Y-axis pointing out of the page.</p>	<p> W_1 = stem width W_2 = cross bar width h_1 = stem height h_2 = cross bar height L = slot length $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

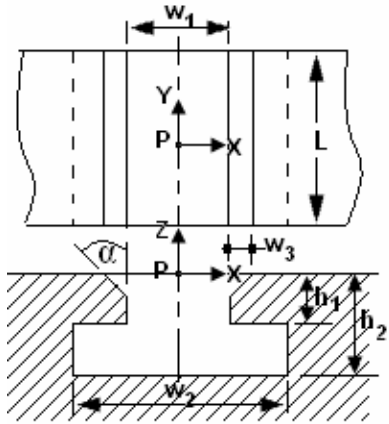
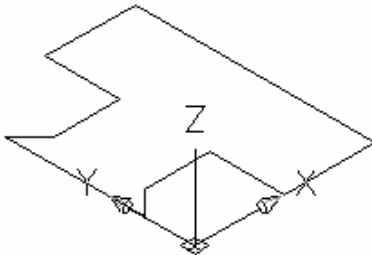
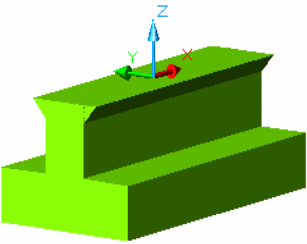
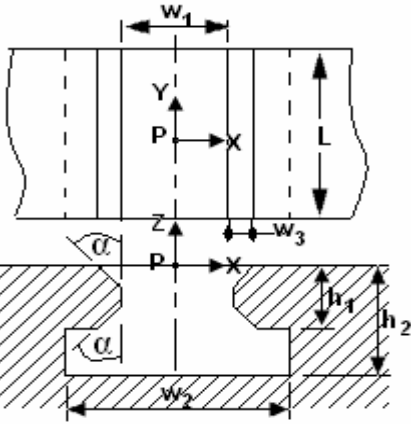
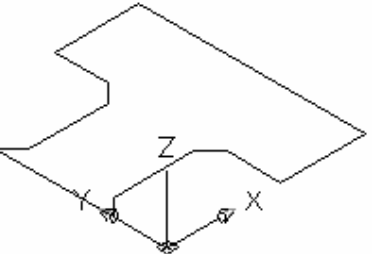
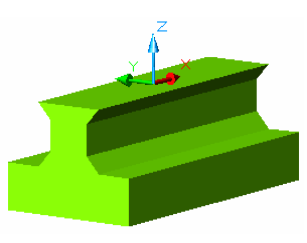
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Tee slot with first chamfers				<p> W_1 = stem width W_2 = cross bar width h_1 = stem height h_2 = cross bar height L = slot length α = chamfer angle W_3 = chamfer width $P(x,y,z)$ = location point </p>
Tee slot with first and second chamfers				<p> W_1 = stem width W_2 = cross bar width h_1 = stem height h_2 = cross bar height L = slot length α = chamfer angle W_3 = chamfer width $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

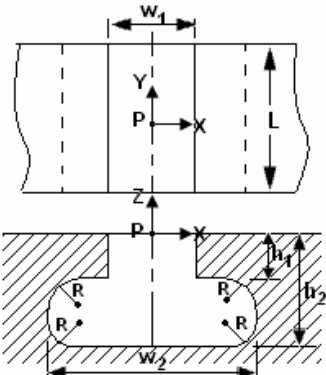
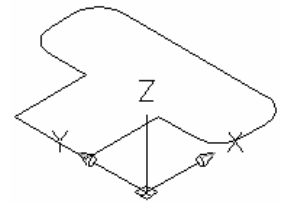
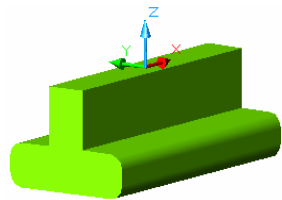
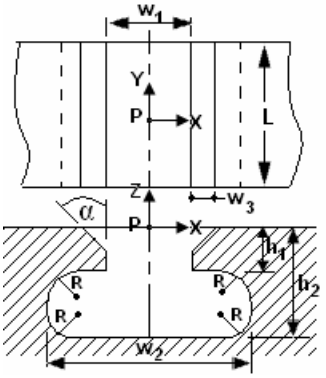
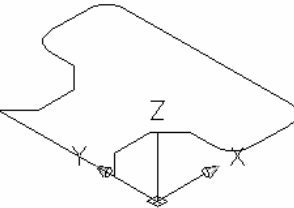
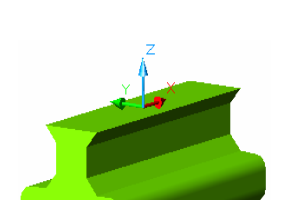
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Tee slot with round corners				<p> W_1 = stem width W_2 = cross bar width h_1 = stem height h_2 = cross bar height L = slot length R = corner radius α = chamfer angle $P(x,y,z)$ = location point </p>
Tee slot with chamfers and round corners				<p> W_1 = stem width W_2 = cross bar width h_1 = stem height h_2 = cross bar height L = slot length R = corner radius α = chamfer angle W_3 = chamfer width $P(x,y,z)$ = location point </p>

Table D.1 (Continued) STEP Features Library

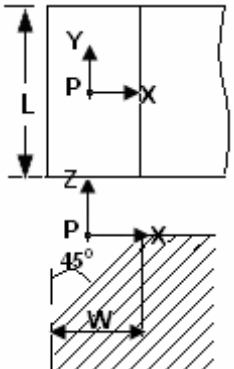
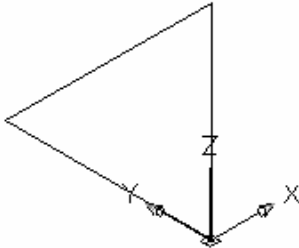
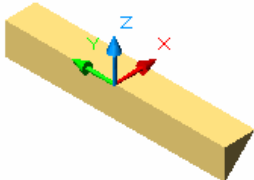
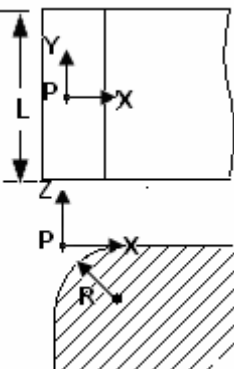
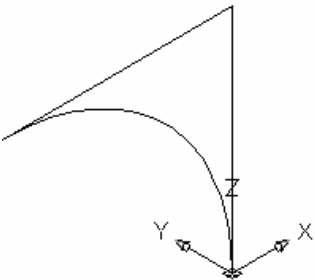
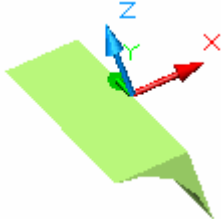
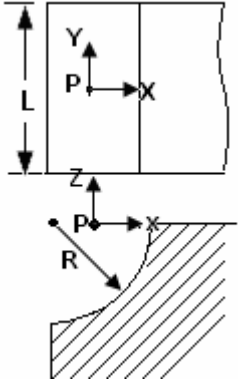
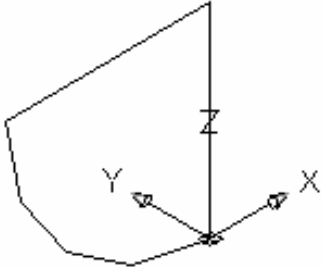
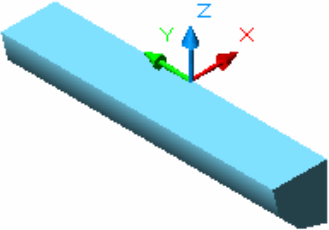
Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Chamfer				<p>L = chamfer length W = chamfer width P(x,y,z) = location point</p>
Edge round				<p>L = edge round length R = edge round radius P(x,y,z) = location point</p>

Table D.1 (Continued) STEP Features Library

Feature name	Feature model	2D feature region	3D feature volume	Feature parameters
Fillet				<p> L = fillet length R = fillet radius $P(x,y,z)$ = location point </p>

APPENDIX E

UML MODELS

This appendix presents UML models of the developed system. Each UML model consists of a number of UML class diagrams connected to each other to show the relationship between these classes. For the demonstration, Figure E.1 shows a UML model of the hole feature. The three classes namely round hole, counterbore hole and countersunk hole are sub-classes of the class hole feature. The class hole feature is a sub-class of the class manufacturing features and defines three types of the hole feature. The round hole feature class contains the properties and operations required to define the round hole feature. It inherits the value of the properties from the other classes like hole bottom condition class, taper select class and linear path class etc. These classes also inherit other classes to assign the values of their properties. For example, hole bottom condition class inherits the spherical hole bottom class to read and write the radius value associated with this class. The other two types of the hole feature, counterbore hole and countersunk hole classes, are defined by two round hole instances. They inherit the round hole class which inherits the other classes to read and write the properties of the two holes.

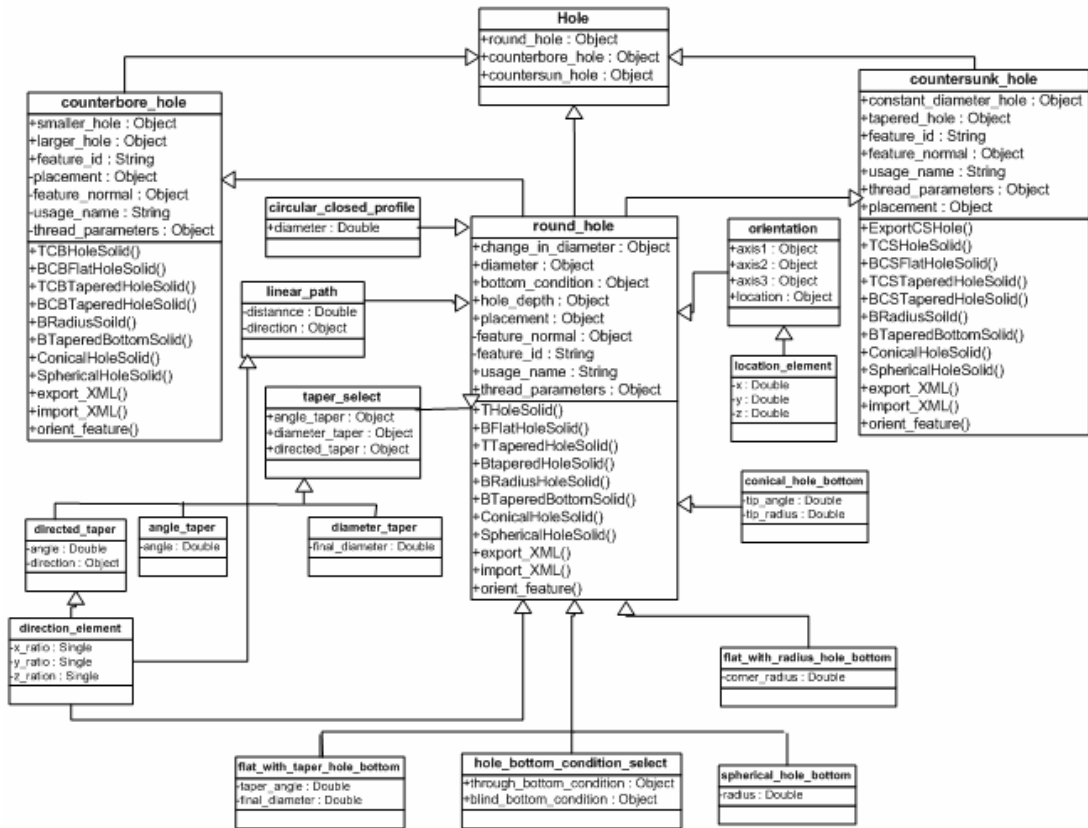


Figure E.1 Hole feature UML model

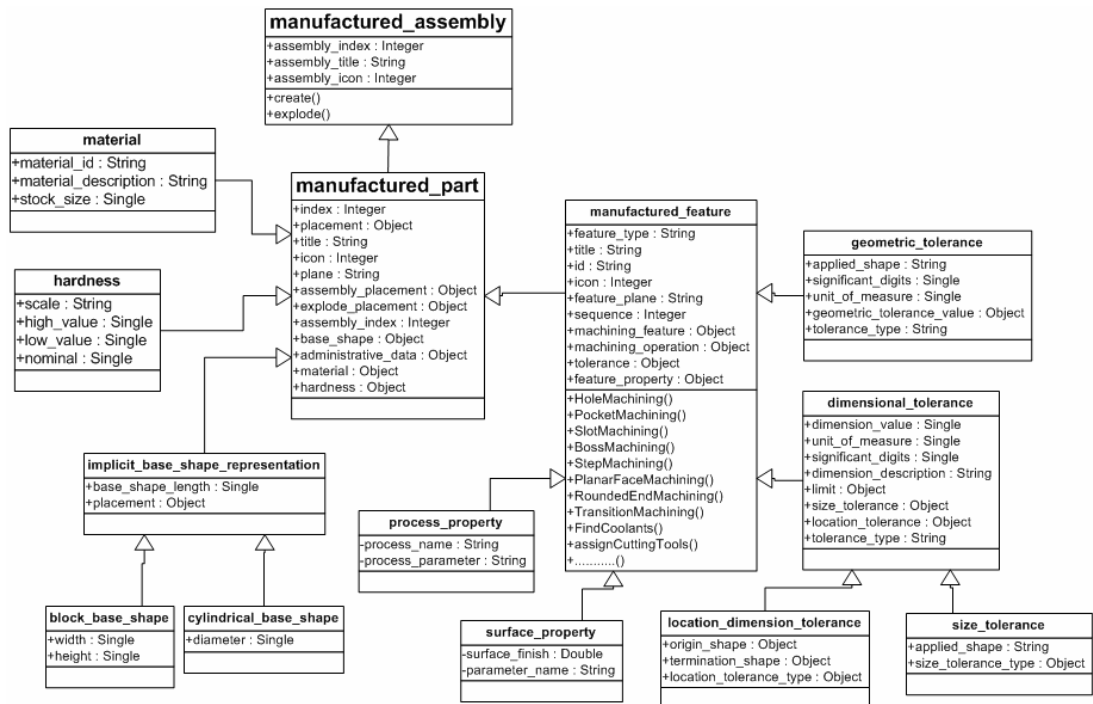


Figure E.2 Manufactured assembly UML model

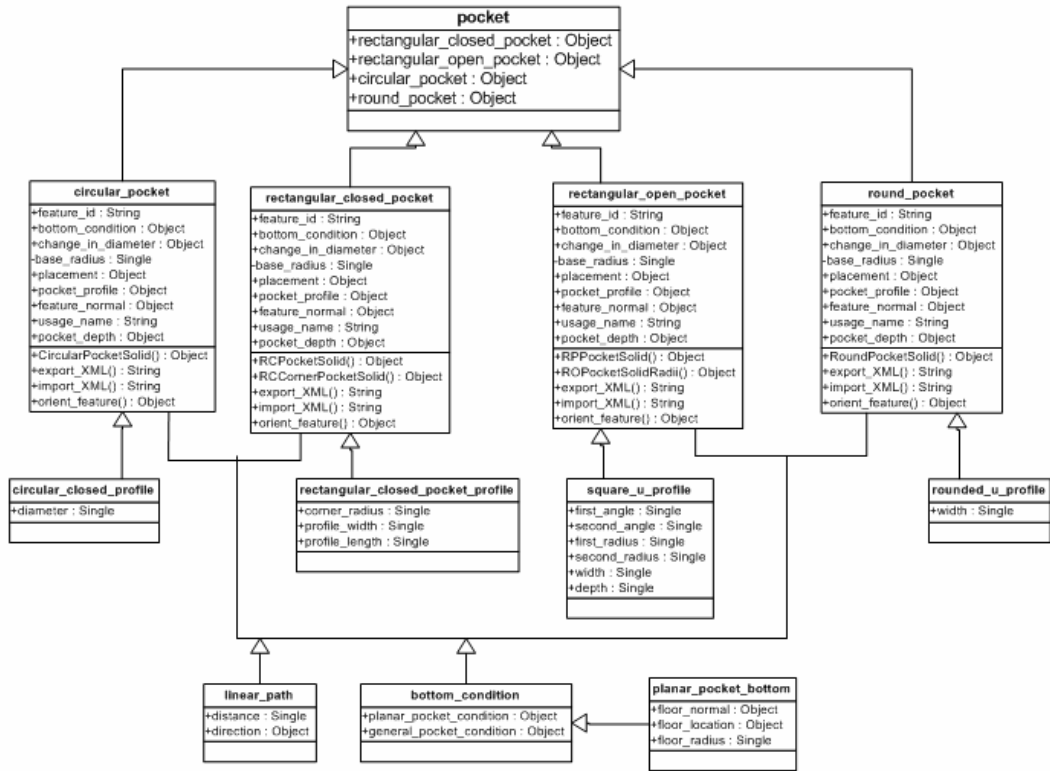


Figure E.3 Pocket feature UML model

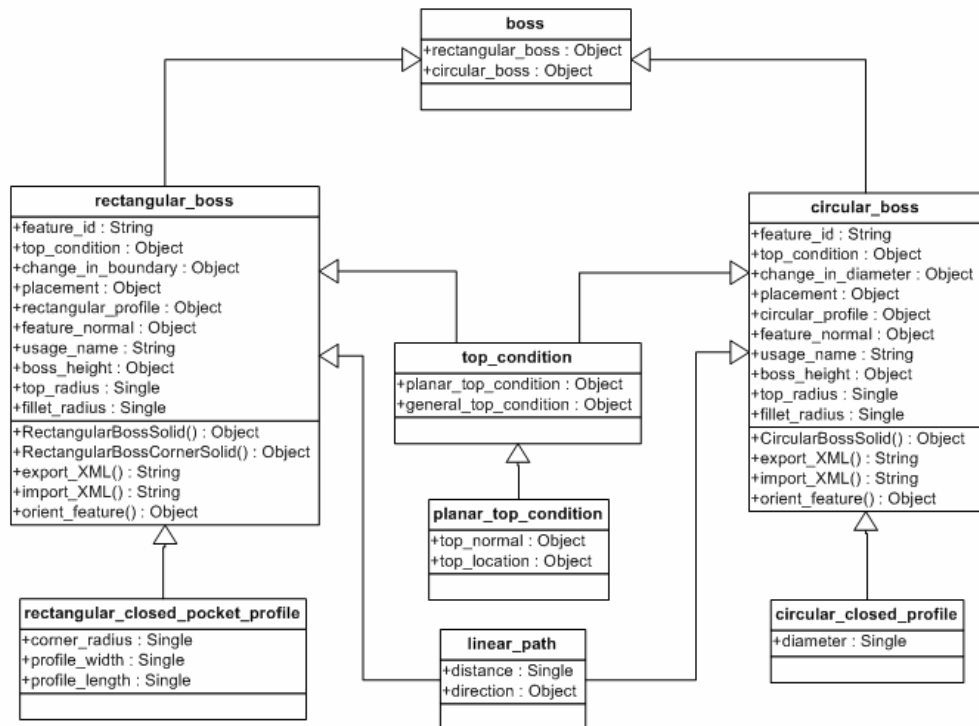


Figure E.4 Boss feature UML model

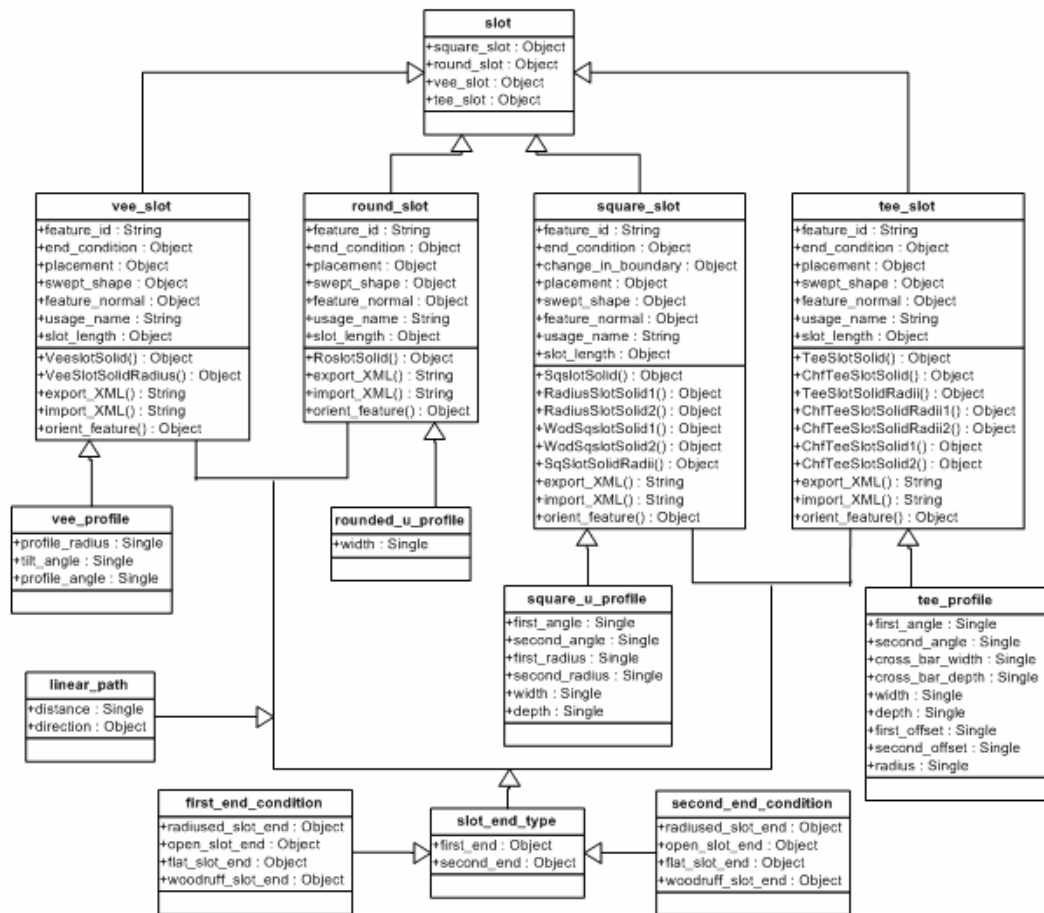


Figure E.5 Slot feature UML model

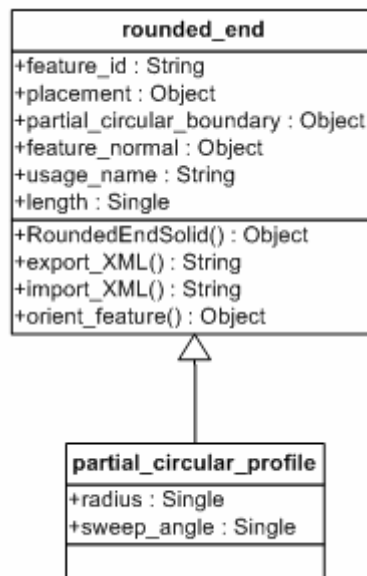


Figure E.6 Rounded end feature UML model

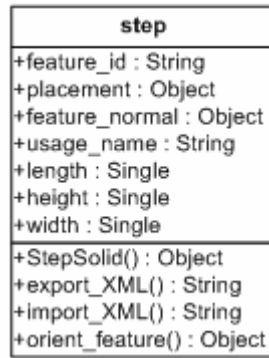


Figure E.7 Step feature UML model

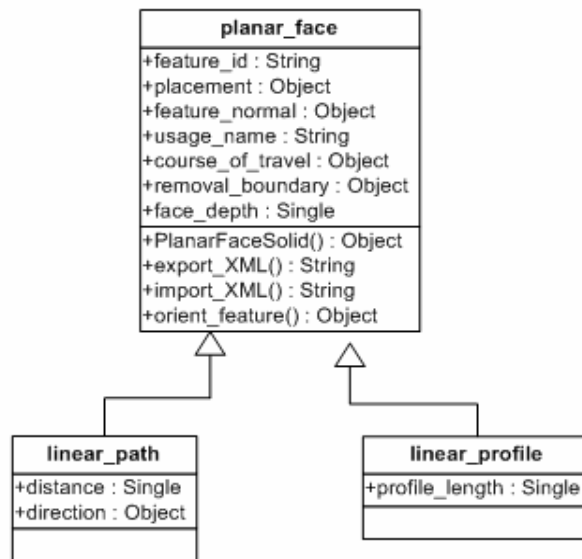


Figure E.8 Planar face feature UML model

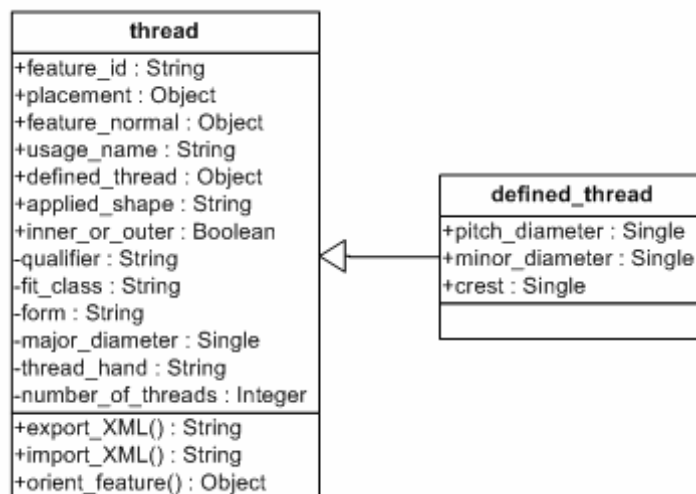


Figure E.9 Thread feature UML model

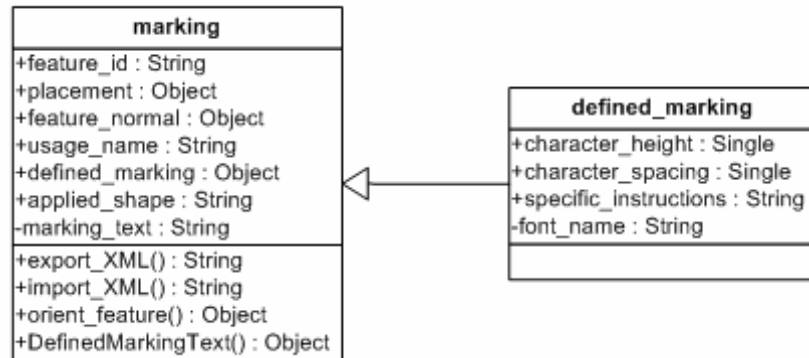


Figure E.10 Marking feature UML model

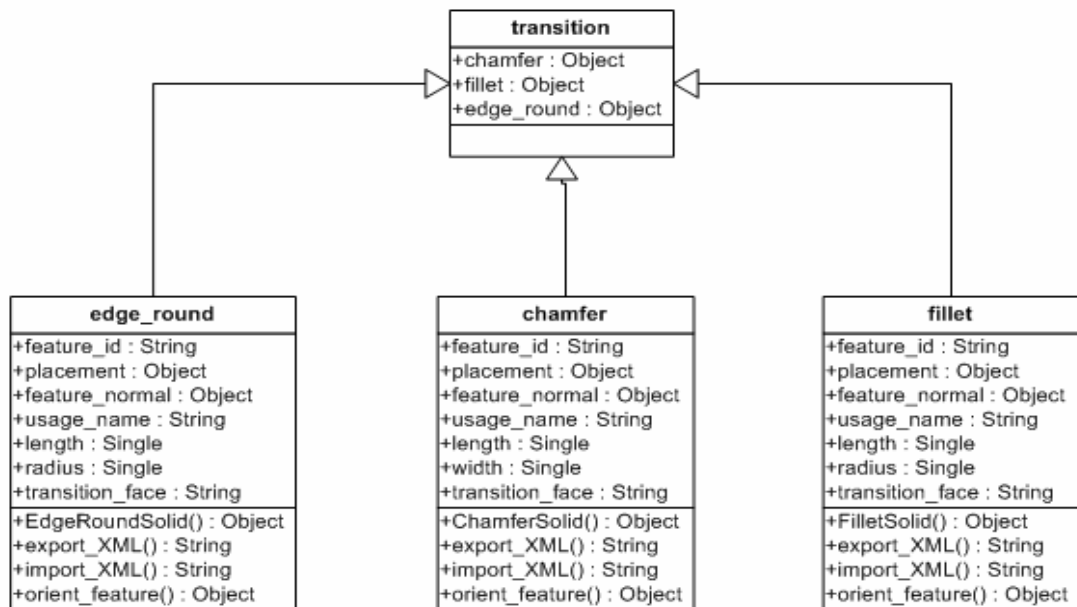


Figure E.11 Transition feature UML model

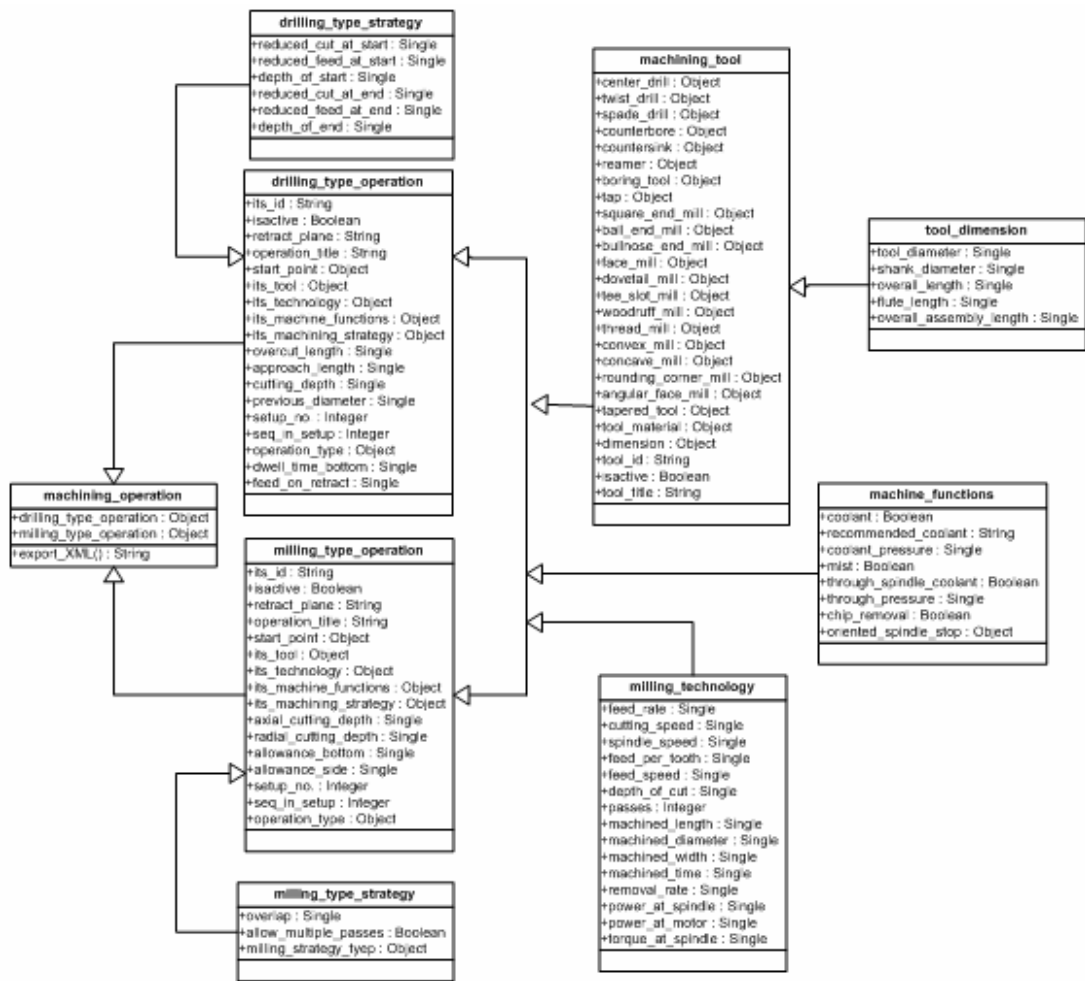


Figure E.12 Machining operation UML model

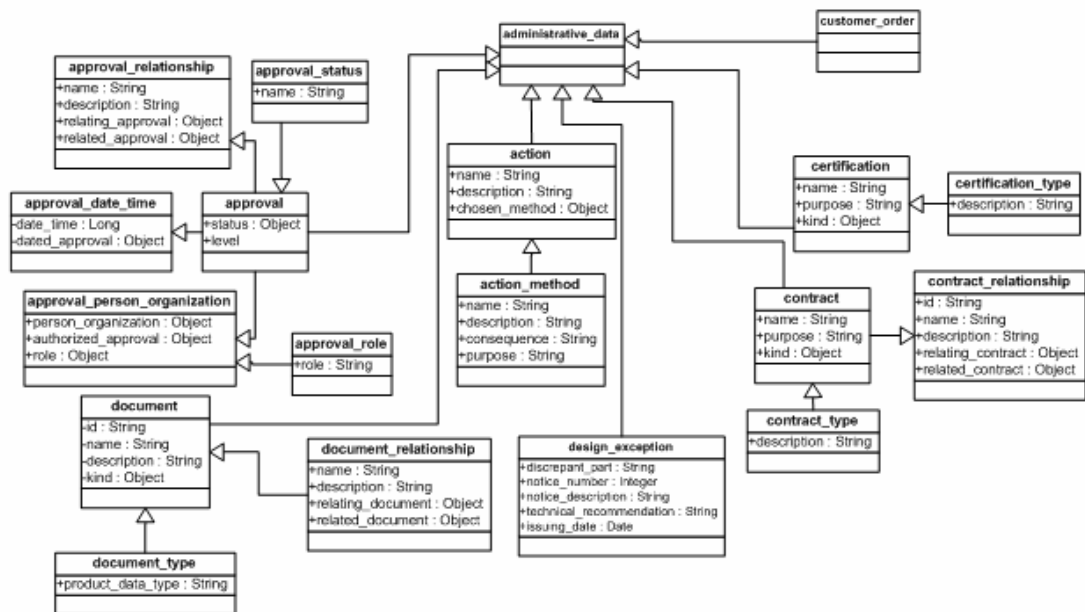


Figure E.13 Administrative data UML model

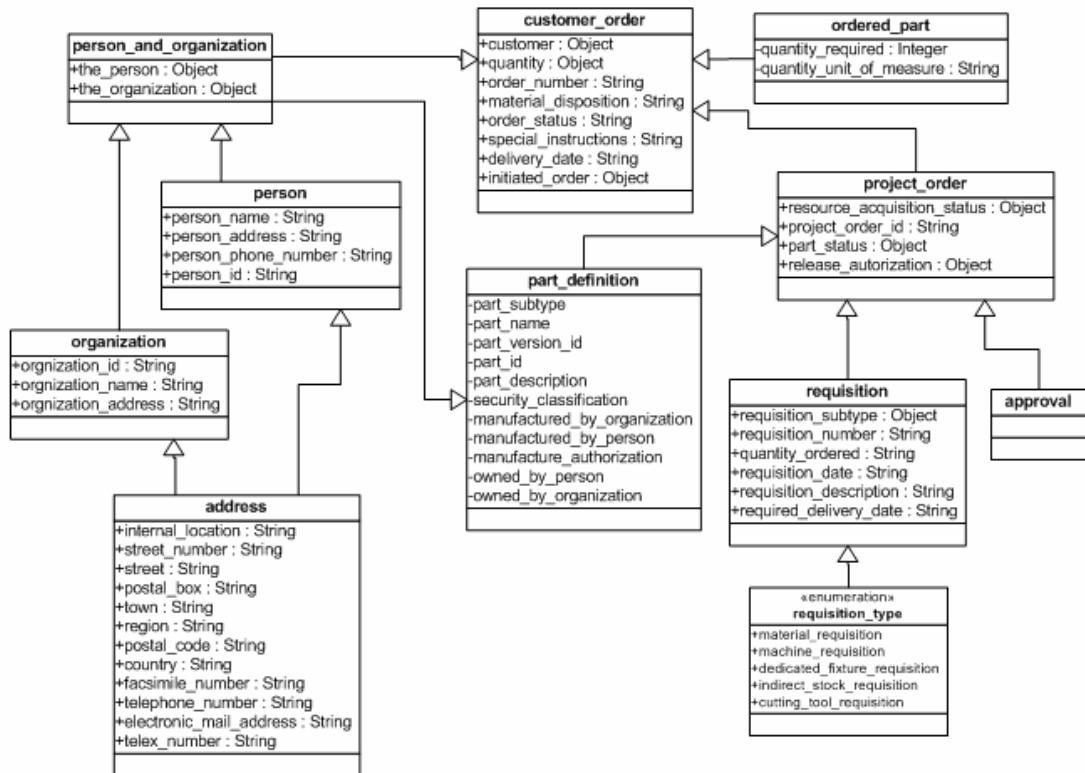


Figure E.14 Customer order UML model

APPENDIX F

STEP-BASED TOLERANCES

Appendix F presents the definitions of STEP-based tolerances and their application to the manufacturing features supported by STEP-FM.

Table F.1 STEP-Based Tolerances

Tolerance Type	Tolerance definition	Tolerance illustration
Dimensional Tolerances		
Angular size dimension tolerance	It specifies the allowable variation on the size or gap formed by two angular elements of the shape.	<p style="text-align: center;">+.004 45 -.005</p>
Curved dimension tolerance	It is a tolerance on a dimension for a curved feature element measured along the entire path of the curve	<p style="text-align: center;">+.002 10.00 -.001</p>
Diameter dimension tolerance	It is the allowable variation of the size of a hole in a feature.	<p style="text-align: center;">+.00y -.00z</p>
Radial dimension tolerance	It is the allowable variation for the radial distance from the center of a feature circular curve to a point on the curve.	<p style="text-align: center;">+.00y -.00z</p>

Table F.1 (Continued) STEP-Based Tolerances

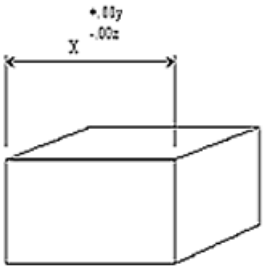
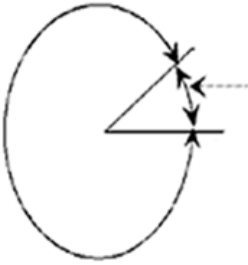
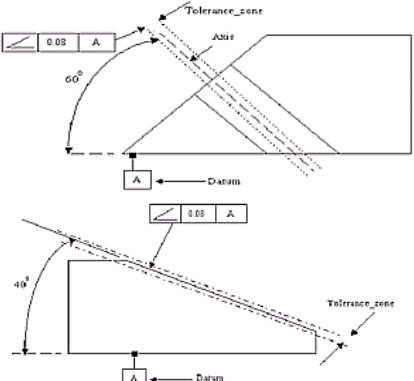
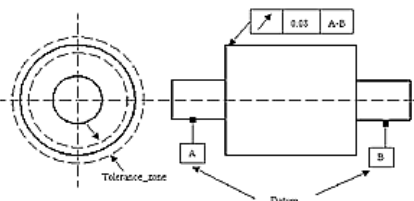
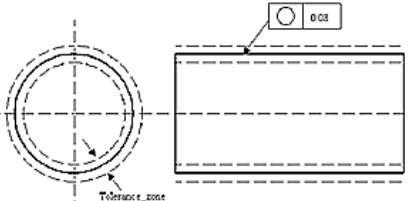
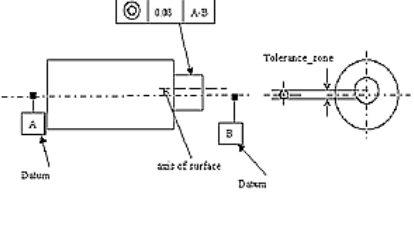
Tolerance Type	Tolerance definition	Tolerance illustration
Location dimension tolerance	It is the allowable variation in locating one feature of a point with respect to another.	
Angular dimension tolerance	It defines the allowable variation in the angle between two elements of a feature.	
Geometrical Tolerances		
Angularity tolerance	It is the allowable variation of a feature surface or axis at a specified angle from a datum plane or axis.	
Circular runout tolerance	It is a tolerance to control circular elements of a feature to a datum axis the feature is rotated about.	
Circularity tolerance	It describes the allowable deviation of a feature surface from round.	
Concentricity tolerance	It is a cylindrical or conical feature of a part which shall be functionally concentric. When the part is rotated about the datum axis, the axis of the feature shall be within the cylindrical tolerance zone.	

Table F.1 (Continued) STEP-Based Tolerances

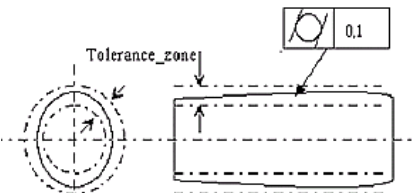
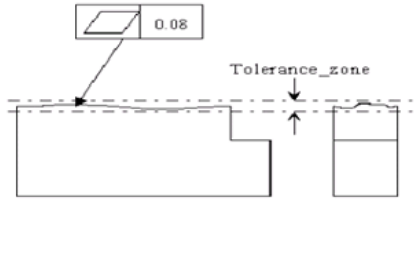
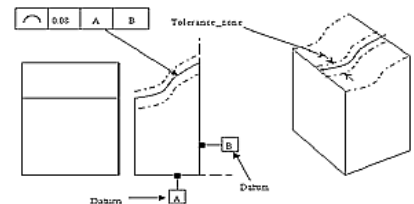
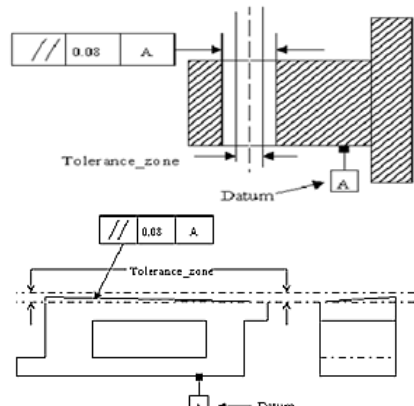
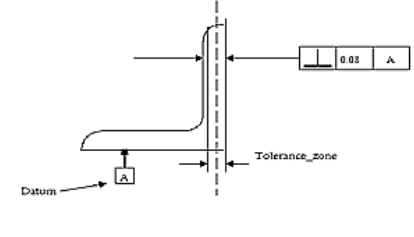
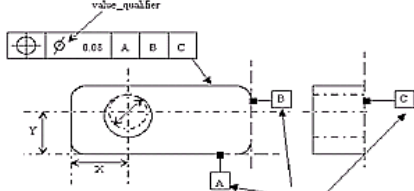
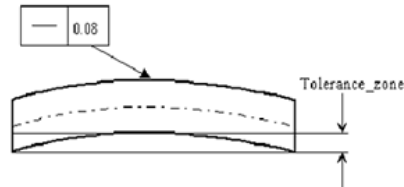
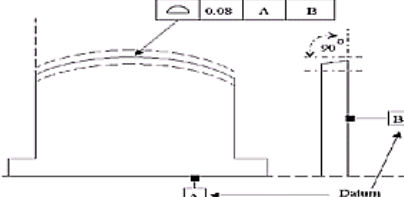
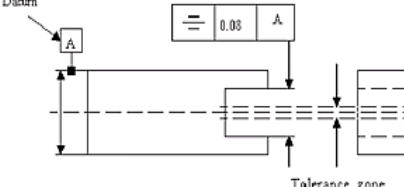
Tolerance Type	Tolerance definition	Tolerance illustration
Cylindricity tolerance	It describes the amount of deviation a feature may have from being truly cylindrical. The feature shall be contained between two coaxial cylinders.	 <p>The diagram shows a cylindrical feature with a tolerance zone of 0.1. The tolerance zone is defined by two coaxial cylinders. The feature is shown in a cross-section and a perspective view. The tolerance zone is indicated by dashed lines and arrows.</p>
Flatness tolerance	It is a tolerance for how much a feature surface is allowed to deviate from being flat. All points of the actual feature surface shall lie between two parallel planes that are a distance equal to the special tolerance.	 <p>The diagram shows a flat surface with a tolerance zone of 0.08. The tolerance zone is defined by two parallel planes. The feature is shown in a perspective view. The tolerance zone is indicated by dashed lines and arrows.</p>
Linear profile tolerance	It is a uniform boundary or zone along the true profile within which all elements of the feature shall lie.	 <p>The diagram shows a curved surface with a tolerance zone of 0.05. The tolerance zone is defined by two profiles relative to datum A and B. The feature is shown in a perspective view. The tolerance zone is indicated by dashed lines and arrows.</p>
Parallelism tolerance	It is the condition of a feature surface equidistant at all points from a datum plane or a feature axis equidistant along its length to a datum axis or plane.	 <p>The diagram shows a surface with a tolerance zone of 0.08. The tolerance zone is defined by two parallel planes relative to datum A. The feature is shown in a perspective view. The tolerance zone is indicated by dashed lines and arrows.</p>
Perpendicularity tolerance	It is the amount of deviation of a feature surface to a perpendicular to a datum. The actual feature surface shall lie within two planes a tolerance apart and perpendicular to a datum surface.	 <p>The diagram shows a surface with a tolerance zone of 0.05. The tolerance zone is defined by two perpendicular planes relative to datum A. The feature is shown in a perspective view. The tolerance zone is indicated by dashed lines and arrows.</p>
Position tolerance	It denotes a tolerance zone for a theoretically exact position of a feature, and is established with respect to a datum.	 <p>The diagram shows a hole with a tolerance zone of 0.05. The tolerance zone is defined by a cylindrical shell relative to datum A, B, and C. The feature is shown in a perspective view. The tolerance zone is indicated by dashed lines and arrows.</p>

Table F.1 (Continued) STEP-Based Tolerances

Tolerance Type	Tolerance definition	Tolerance illustration
<p>Straightness tolerance</p>	<p>It is the amount of deviation a feature surface shall have from being straight.</p>	 <p>The diagram shows a curved surface with a tolerance feature control frame containing a straightness symbol and a tolerance value of 0.08. A vertical double-headed arrow labeled 'Tolerance_zone' indicates the maximum deviation from a straight line.</p>
<p>Surface profile tolerance</p>	<p>It is a uniform boundary or zone along the true profile with which all elements of the feature surface shall lie.</p>	 <p>The diagram shows a stepped shaft with a surface profile tolerance feature control frame containing a surface profile symbol, a tolerance value of 0.08, and datum letters A and B. Datum A is the cylindrical surface, and datum B is the vertical end face. A 90-degree angle is shown between datum B and datum A. A vertical double-headed arrow labeled 'Tolerance_zone' indicates the deviation from the true profile.</p>
<p>Symmetry tolerance</p>	<p>It is the amount of deviation a feature surface shall have from being symmetrical to a datum.</p>	 <p>The diagram shows a shaft with a symmetry tolerance feature control frame containing a symmetry symbol, a tolerance value of 0.08, and datum letter A. Datum A is the cylindrical surface. A vertical double-headed arrow labeled 'Tolerance_zone' indicates the deviation from a plane of symmetry.</p>

APPENDIX G

NEURAL NETWORKS TRAINING EXPERIMENTS

Table G.1 Training experiments data of the neural networks implemented in ST-FeatCAPP

Exp. No.	Network Name	Inputs	Outputs	Hidden Layers	Hidden neurons	η	α	Train pattern	epoch	sse
1	Hole	6	8	2	15	0.1	0.9	432	3000	0.0201
2	Hole	6	8	2	15	0.3	0.8	432	2179	0.00001
3	Hole	6	8	2	15	0.5	0.7	432	2907	0.00001
4	Hole	6	8	2	12	0.3	0.8	432	3000	0.19
5	Hole	6	8	2	12	0.1	0.9	432	3000	0.000015
6	Slot	6	6	2	15	0.3	0.8	224	3000	0.000018
7	Slot	6	6	2	15	0.1	0.9	224	3000	0.000016
8	Slot	6	6	2	15	0.4	0.6	224	3000	0.000028
9	Slot	6	6	2	10	0.1	0.9	224	3000	0.000025
10	Slot	6	6	2	10	0.25	0.8	224	3000	0.19
11	Pocket	6	6	2	15	0.3	0.8	168	429	0.00001
12	Pocket	6	6	2	15	0.1	0.9	168	584	0.00001
13	Pocket	6	6	2	15	0.4	0.6	168	620	0.00001
14	Pocket	6	6	2	10	0.1	0.9	168	853	0.00001
15	Pocket	6	6	2	10	0.25	0.8	168	606	0.00001
16	Boss	6	6	2	15	0.3	0.8	108	691	0.00001
17	Boss	6	6	2	15	0.1	0.9	108	933	0.00001
18	Boss	6	6	2	15	0.4	0.6	108	1000	0.00001
19	Boss	6	6	2	10	0.1	0.9	108	1030	0.00001
20	Boss	6	6	2	10	0.25	0.8	108	969	0.00001
21	Transition	6	6	2	15	0.3	0.8	144	569	0.00001
22	Transition	6	6	2	15	0.1	0.9	144	867	0.00001
23	Transition	6	6	2	15	0.4	0.6	144	873	0.00001
24	Transition	6	6	2	10	0.1	0.9	144	876	0.00001
25	Transition	6	6	2	10	0.25	0.8	144	741	0.00001
26	Step	6	6	2	15	0.3	0.8	96	883	0.00001
27	Step	6	6	2	15	0.1	0.9	96	1165	0.00001
28	Step	6	6	2	15	0.4	0.6	96	1299	0.00001
29	Step	6	6	2	10	0.1	0.9	96	1493	0.00001
30	Step	6	6	2	10	0.25	0.8	96	1225	0.00001
31	Planar face	6	6	2	15	0.3	0.8	96	826	0.00001
32	Planar face	6	6	2	15	0.1	0.9	96	2000	0.00001
33	Planar face	6	6	2	15	0.4	0.6	96	1299	0.00001
34	Planar face	6	6	2	10	0.1	0.9	96	1861	0.00001
35	Planar face	6	6	2	10	0.25	0.8	96	1114	0.00001

Table G.1 (Continued) Training experiments data of the neural networks implemented in ST-FeatCAPP

Exp. No.	Network Name	Inputs	Outputs	Hidden Layers	Hidden neurons	η	α	Train pattern	epoch	sse
36	Rounded end	6	6	2	15	0.3	0.8	96	865	0.00001
37	Rounded end	6	6	2	15	0.1	0.9	96	1225	0.00001
38	Rounded end	6	6	2	15	0.4	0.6	96	1320	0.00001
39	Rounded end	6	6	2	10	0.1	0.9	96	1312	0.00001
40	Rounded end	6	6	2	10	0.25	0.8	96	1118	0.00001
41	Twist drill	2	9	2	12	0.1	0.9	135	3000	0.000217
42	Twist drill	2	9	2	12	0.3	0.8	135	3000	0.00018
43	Twist drill	2	9	2	12	0.4	0.6	135	3000	0.00018
44	Twist drill	2	9	2	15	0.3	0.7	135	3000	0.00019
45	Twist drill	2	9	2	15	0.2	0.9	135	3000	0.00017
46	Drilling tools	5	12	2	15	0.1	0.9	198	2000	0.00019
47	Drilling tools	5	12	2	15	0.3	0.8	198	2000	0.091
48	Drilling tools	5	12	2	15	0.1	0.7	198	2000	0.00137
49	Drilling tools	5	12	2	15	0.25	0.9	198	2000	0.39
50	Drilling tools	5	12	2	12	0.1	0.9	198	2000	0.0254
51	Milling tools	5	13	2	15	0.1	0.9	74	2000	0.0271
52	Milling tools	5	13	2	15	0.3	0.8	74	2000	0.000082
53	Milling tools	5	13	2	15	0.4	0.7	74	2000	0.000104
54	Milling tools	5	13	2	15	0.1	0.8	74	2000	0.00034
55	Milling tools	5	13	2	12	0.5	0.5	74	2000	0.00015
56	Reamer	2	10	2	15	0.1	0.9	122	3000	0.000744
57	Reamer	2	10	2	15	0.3	0.8	122	3000	0.00072
58	Reamer	2	10	2	15	0.3	0.9	122	3000	0.00083
59	Reamer	2	10	2	15	0.4	0.7	122	3000	0.00073
60	Reamer	2	10	2	15	0.25	0.8	122	3000	0.00074

Table G.1 (Continued) Training experiments data of the neural networks implemented in ST-FeatCAPP

Exp. No.	Network Name	Inputs	Outputs	Hidden Layers	Hidden neurons	η	α	Train pattern	epoch	sse
61	Spade drill	3	7	2	10	0.1	0.9	183	3000	0.0058
62	Spade drill	3	7	2	10	0.25	0.8	183	3000	0.0036
63	Spade drill	3	7	2	15	0.3	0.8	183	3000	0.0039
64	Spade drill	3	7	2	15	0.1	0.7	183	3000	0.0063
65	Spade drill	3	7	2	15	0.2	0.8	183	3000	0.00326
66	End mill	3	7	2	15	0.1	0.9	324	3000	0.0059
67	End mill	3	7	2	15	0.3	0.8	324	3000	0.00019
68	End mill	3	7	2	15	0.2	0.7	324	3000	0.00034
69	End mill	3	7	2	15	0.5	0.8	324	3000	0.00012
70	End mill	3	7	2	15	0.4	0.7	324	3000	0.00024
71	Milling cutters	3	6	2	15	0.1	0.9	189	2000	0.00047
72	Milling cutters	3	6	2	15	0.3	0.8	189	405	0.00001
73	Milling cutters	3	6	2	15	0.4	0.6	189	370	0.00001
74	Milling cutters	3	6	2	15	0.4	0.9	189	485	0.00001
75	Milling cutters	3	6	2	15	0.6	0.2	189	453	0.00001

Where

η is the learning rate.

α is the momentum

sse is the average sum-square error

APPENDIX H

FUZZY LOGIC KNOWLEDGE BASE

This appendix contains the fuzzy knowledge base in a tabulated format. Tables H1 to H8 present the the fuzzy rules utilized by the developed fuzzy models.

The workpiece material codes used in the tables are defined as follows:

- 1= Free machining carbon steel,
- 2= Carbon steel,
- 3= Alloy steel,
- 4= Stainless steel,
- 5= Gray cast iron,
- 6= Ductile cast iron,
- 7= Malleable cast iron,
- 8= Aluminium alloys,
- 9= Copper alloys.

Table H.1 Fuzzy Rule Knowledge Base for Twist Drilling Machining Parameters Selection using HSS Tool Material

			Tool Diameter																																																					
			Very Small									Small									Medium									Large									Very Large																	
			Workpiece Material																																																					
			1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9									
Material Hardness	Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F									
	Very Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F									
	Medium	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	M	M	M	M	S	S	S	S	S	S	M	M	M	M	S	S	S	S	S	S	M	M	M								
	Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S									
	Very Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S									

Table H.2 Fuzzy Rule Knowledge Base for Spade Drilling Machining Parameters Selection using HSS Tool Material

			Tool Diameter																																																					
			Very Small									Small									Medium									Large									Very Large																	
			Workpiece Material																																																					
			1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9									
Material Hardness	Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F									
	Very Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F									
	Medium	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F									
	Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S									
	Very Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S									

Table H.5 Fuzzy Rule Knowledge Base for Boring Machining Parameters Selection using HSS Tool Material

			Tool Diameter																																																		
			Very Small									Small									Medium									Large									Very Large														
			Workpiece Material																																																		
			1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9						
Material Hardness	Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M								
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F			
	Very Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M							
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	
	Medium	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M							
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M							
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	Very Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M							
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

Table H.6 Fuzzy Rule Knowledge Base for Tapping Machining Parameters Selection using HSS Tool Material

			Tool Diameter																																																		
			Very Small									Small									Medium									Large									Very Large														
			Workpiece Material																																																		
			1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9						
Material Hardness	Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M								
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	Very Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M								
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	Medium	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M								
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	M	M	M	M	M	F	F	F	F	M	M	M	M	M	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M								
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	Very Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M								
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

Table H.7 Fuzzy Rule Knowledge Base for Side Milling Machining Parameters Selection using HSS Tool Material

		Tool Diameter																																																
		Very Small									Small									Medium									Large									Very Large												
		Workpiece Material																																																
		1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9				
Material Hardness	Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	M	F	F	F	F	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	Very Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	M	F	F	F	F	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	Medium	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	M	F	F	F	F	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	Very Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

Table H.8 Fuzzy Rule Knowledge Base for Bottom and Side Milling Machining Parameters Selection using HSS Tool Material

		Tool Diameter																																																
		Very Small									Small									Medium									Large									Very Large												
		Workpiece Material																																																
		1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9				
Material Hardness	Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	M	F	F	F	F	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	Very Soft	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	M	F	F	F	F	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	Medium	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	M	M	M	M	M	M	F	F	F	F	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	Very Hard	v	M	M	L	L	L	L	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M	M	M	M	L	L	L	L	M	M	M
		f	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S	S	S	S	VS	VS	VS	VS	VS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

APPENDIX I

CUTTING TOOLS LIBRARY

Table I.1 Cutting Tools library



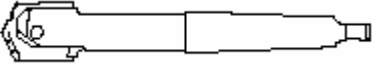


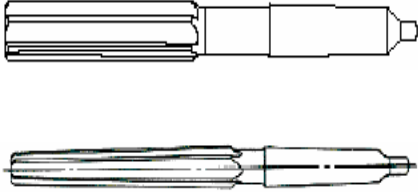
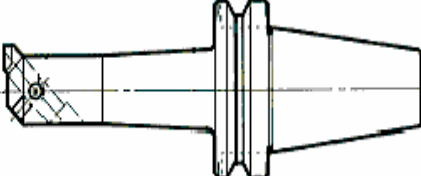
Cutting Tool	Tool definition	Tool body figure
Center drill	A center drill is used to center a tool shaft prior to cutting.	
Twist drill	A twist drill is a drill having one or more cutting lips and one or more straight or helical flutes for the passage of chips and cutting fluids.	 <p style="text-align: center;"><i>Tapered twist drill</i></p>
Spade drill	A spade drill is a drill capable of producing large deep holes with a variety of bottom profiles. A spade drill typically consists of a removable blade or tip clamped in a holder on the drill shank.	
Counterbore	A counterbore is a drill capable of enlarging the opening of a previously formed hole.	
Countersink	A countersink is a drill capable of cutting a tapered enlargement at the opening of a hole.	
Reamer	A reamer is a multiple-cutting-edge tool used to enlarge or finish round holes, to give accurate dimensions as well as reduced surface roughness. The cutting edges of a reamer can be both on the end and on the periphery.	 <p style="text-align: center;"><i>Tapered reamer</i></p>
Boring tool	A boring tool is a single point cutting tool used to enlarge or finish internal holes coaxial with the boring tool axis. The cutting point(s) of the boring tool can be used singly or in pairs.	

Table I.1 (Continued) Cutting Tools Library

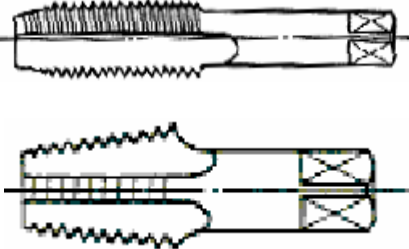
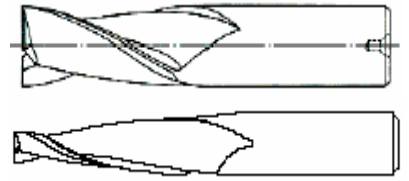


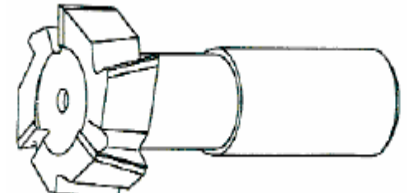
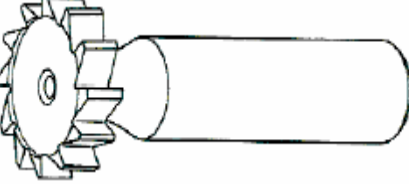
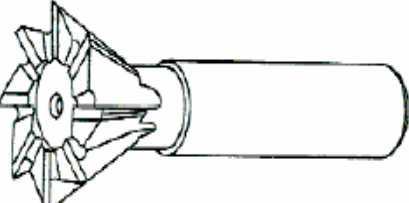


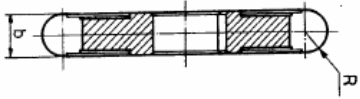
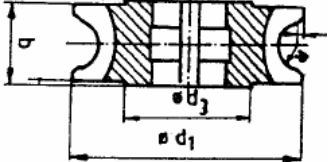
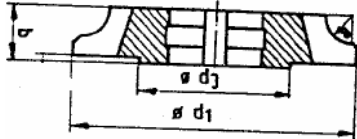
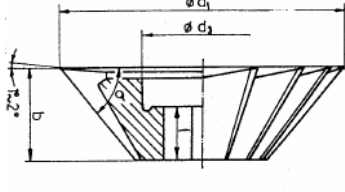
Cutting Tool	Tool definition	Tool body figure
Tap	A tap is a rotary cutting tool with multiple cutting teeth used to produce internal threads.	 <p style="text-align: center;"><i>Tapered tap</i></p>
End Mill	An end mill is a cylindrical milling cutter capable of cutting on the end and on the periphery.	 <p style="text-align: center;"><i>Tapered end mill</i></p>
Ball end mill	-	
Bullnose end mill	-	
T-slot mill	A T-slot mill is a milling cutter used to produce "T" shaped slots through surfaces perpendicular to the tool axis.	
woodruff keyseat mill	A woodruff keyseat mill is a milling cutter used to produce a slot with a rectangular cross-section perpendicular to the tool axis and a circular-arc cross-section parallel to the tool axis.	
Dovetail mill	A dovetail mill is a milling cutter used to produce dovetail-shaped slots through a surface perpendicular to the tool axis.	

Table I.1 (Continued) Cutting Tools Library

Cutting Tool	Tool definition	Tool body figure
Thread mill	A thread mill is a milling cutter having cutting edges capable of Producing "V" shaped slots.	
Face mill	A face mill is a milling cutter used for machining large surfaces perpendicular to the tool axis.	
Convex mill	A convex mill is a milling cutter used for machining fillets and radii.	
Concave mill	A concave mill is a milling cutter capable of producing round corners and ends.	
Rounding corner mill	A rounding corner mill is a milling cutter used for machining round edges.	
Angular face mill	An angular face mill is a milling cutter capable of producing chamfers and inclined surfaces.	

APPENDIX J

ST-FeatCAPP SYSTEM MENUS AND TOOLBARS

J.1 ST-FeatCAPP Pull-down Menus

The pull-down menus in ST-FeatCAPP include the ST-FeatCAPP and AutoCAD functions. Almost all of the functionalities available in ST-FeatCAPP and AutoCAD can be accessed through the pull-down menus. The following subsections provide a short description of the contents of some pull-down menus of the system.

J.1.1 File menu

The File menu is a standard menu contains the most used file management commands. Figure J.1 shows the contents of the file menu.

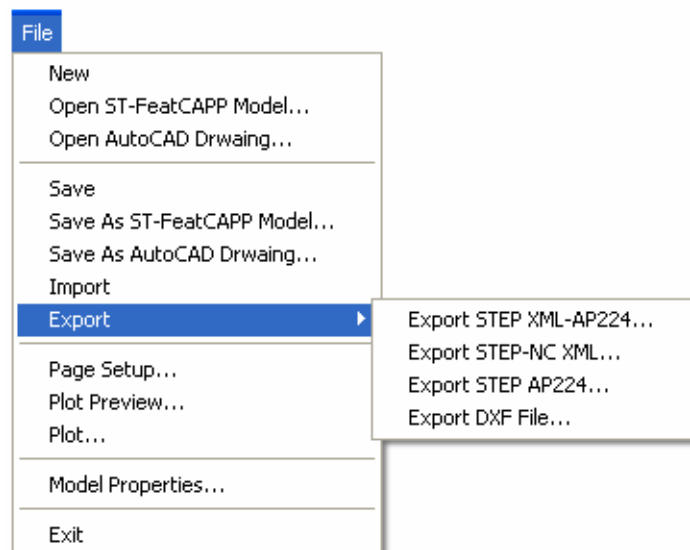


Figure J.1 File menu

- **New.** To create a new part mode.
- **Open ST-FeatCAPP model.** To load an existing ST-FeatCAPP model.
- **Open AutoCAD drawing.** To load an existing AutoCAD drawing.
- **Save as ST-FeatCAPP model.** To save the designed part in ST-FeatCAPP format.
- **Save as AutoCAD drawing.** To save the designed part in AutoCAD format.
- **Import.** To import STEP-AP224 XML or DXF files to the system.
- **Export STEP-AP224 XML.** To generate the design data of the part according to STEP-AP224 and save it in XML format.
- **Export STEP-NC XML.** To generate the manufacturing data of the part according to STEP-NC (ISO 14649 & ISO 10303-AP238) and save it in XML format based on STEP-part 28.
- **Export STEP-AP224.** To generate the design data of the part according to STEP-AP-224 and save it in
- **Export DXF.** To generate the DXF data format of the part using AutoCAD DXFout function.

J.1.2 Features menu

Features menu contains commands to view feature properties, modify attached feature and attach features to the main part. Figure J.2 shows the feature menu and its submenus.

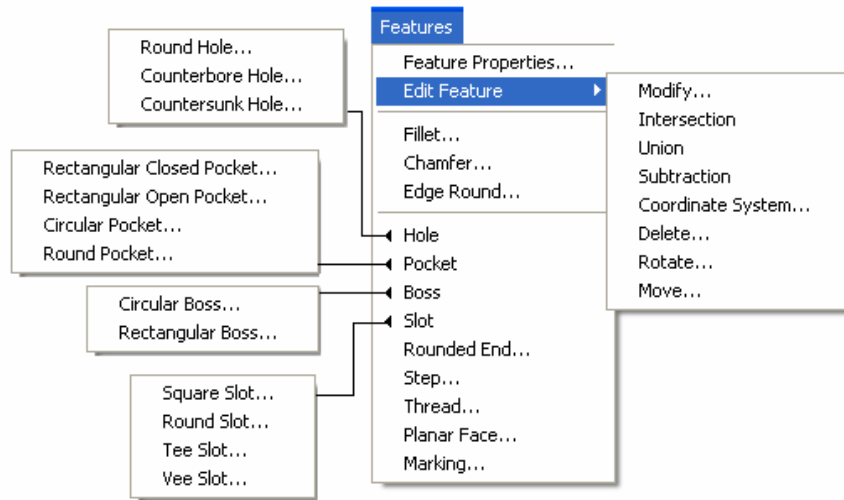


Figure J.2 Features menu

- **Feature properties.** To view the attached features and their properties.
- **Edit feature.** To modify, delete, rotate, move, or perform boolean operations on the existing features.
- **Fillet.** To attach a fillet feature to the main part.
- **Chamfer.** To attach a chamfer feature to the main part.
- **Edge round.** To attach an edge round feature to the main part.
- **Hole.** To attach a round hole, counterbore or countersunk hole feature to the main part.
- **Pocket.** To attach a rectangular closed or open pocket, circular pocket, or round pocket feature to the main part.
- **Boss.** To attach a circular or rectangular boss feature to the main part.
- **Slot.** To attach a square slot, round slot, tee slot, or vee slot feature to the main part.
- **Rounded end.** To attach a rounded end feature to the main part.
- **Step.** To attach a step feature to the main part.
- **Thread.** To attach a thread feature to an attached feature on the main part.
- **Planar face.** To attach a planar face feature to the main part.
- **Marking.** To attach a marking feature to an attached feature on the main part.

J.1.3 Tolerances menu

Tolerances menu contains the commands used to assign dimensional and geometrical tolerances to the attached features. Figure J.3 shows the tolerances menu contents.

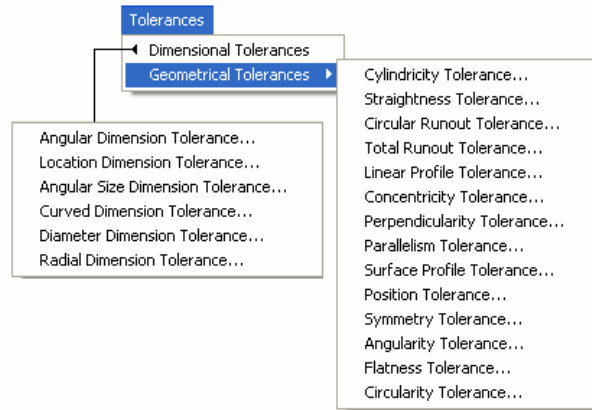


Figure J.3 Tolerances menu

- **Dimensional tolerances.** To assign dimensional tolerances to a feature attached to the main part.
- **Geometrical tolerances.** To assign geometrical tolerances to a feature attached to the main part.

J.1.4 Machining menu

Machining menu contains the process planning commands used to call the process planning tasks of ST-FeatCAPP system. Figure J.4 shows the machining menu and its submenus.

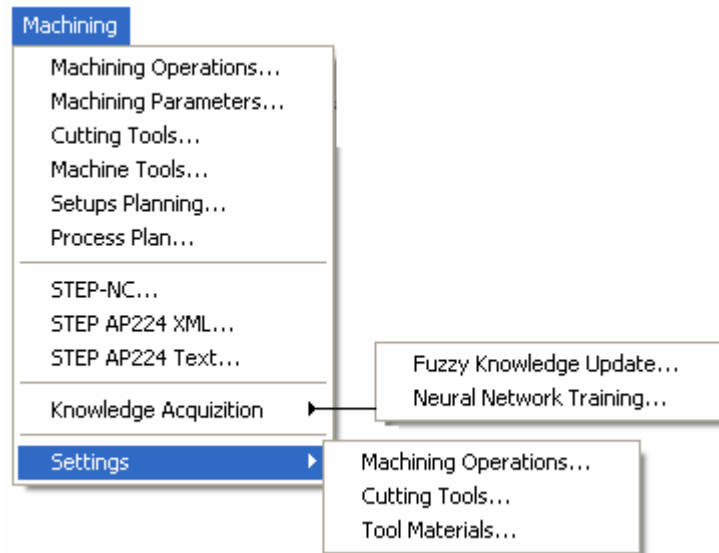


Figure J.4 Machining menu

- **Machining operations.** To select and display the machining operations for the manufactured part.
- **Machining parameters.** To select and display the machining parameters for each machining operation selected to machine the part.
- **Cutting tools.** To select and display the required cutting tools needed for each machining operation.
- **Machine tools.** To select and display the recommended machine tool data for machining the manufactured part.
- **Setup planning.** To generate and display the necessary setup plans for machining the manufactured part.
- **Process plan.** To display the process plan for all machining operations and their parameters required for machining the part.
- **STEP-NC.** To display the manufacturing data according to STEP-NC standard in XML format.
- **STEP AP224 XML.** To display the design data according to STEP AP224 standard in XML format.
- **STEP AP224 Text.** To display the design data according to STEP AP224 standard in text format.

- **Knowldeg acquisition.** To learn and update the neural newtoks and fuzzy lofic knowledge-base respectively.
- **Settings.** To set the default values of the machining operation attributes, view the cutting tools library, and to adjust the tool materials.

J.1.5 Part menu

Part menu contains the functions related to part base shape, assembly, material, properties, and data management. Figure J.5 shows the part menu of ST-FeatCAPP system.

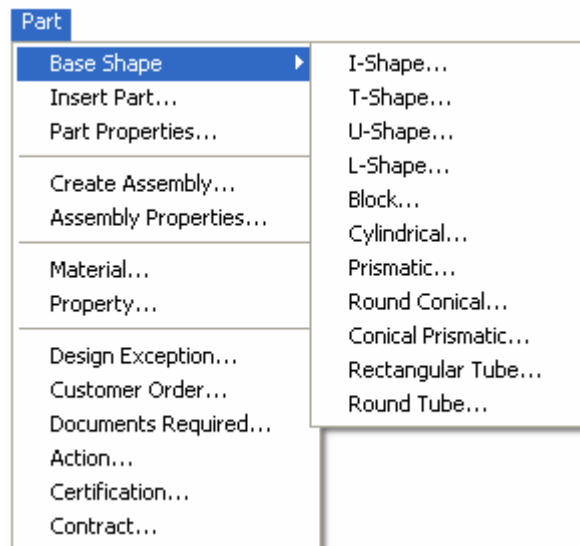


Figure J.5 Part menu

- **Base shape.** To select the base shape of the initial stock of the manufactured part and define its geometrical dimensions..
- **Insert part.** To insert an existing manufactured part into the model space for assembly purpose.
- **Part properties.** To display the part properties during the modeling process.
- **Create assembly.** To create a new manufactured assembly.
- **Assembly properties.** To display the created manufactured assembly properties and view the parts assembly data.

- **Material.** To assign the part material, stock size and material hardness.
- **Property.** To assign a process needed to be performed on the part and assign the surface finish of the part.
- **Design exception.** To provide information about problems resulted during creation of the process plan.
- **Customer order.** To collect information about the customer and the ordered quantity.
- **Documents required.** To provide information about the documents required to support the part manufacturing.
- **Action.** To assign actions to be carried out on the manufactured part.
- **Certification.** To place a certification for a certain tasks.
- **Contract.** To provide information about the contract.

J.2 ST-FeatCAPP Toolbars

ST-FeatCAPP provides several toolbars for access to frequently used functions. These toolbars are displayed by default when the system starts. The following figures show a short description of the contents of each toolbar.

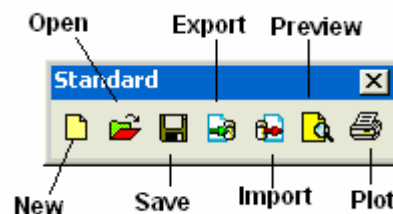


Figure J.6 Standard toolbar

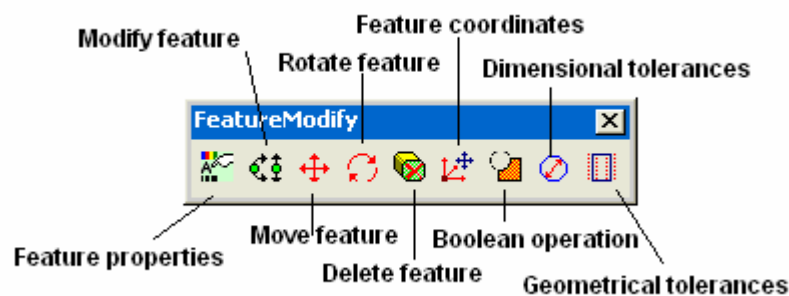


Figure J.7 Feature modify toolbar

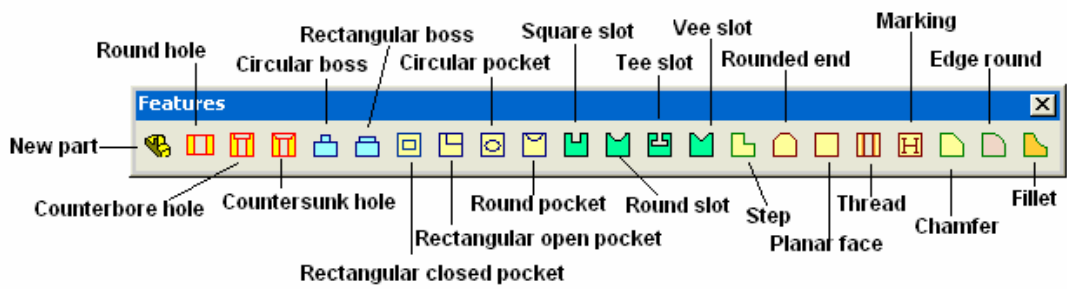


Figure J.8 Features toolbar

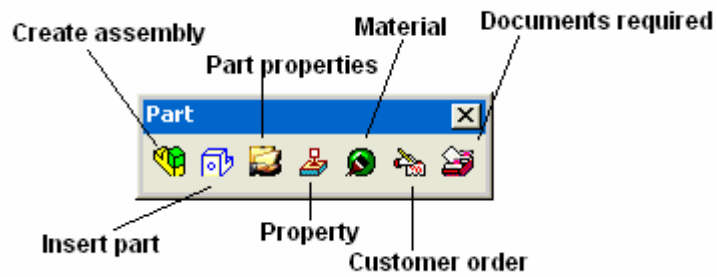


Figure J.9 Part toolbar

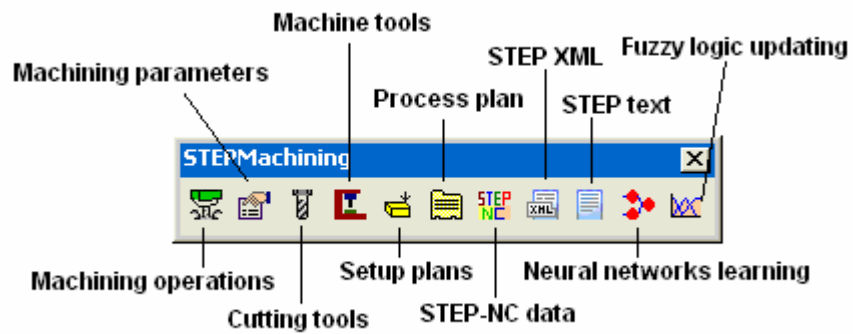


Figure J.10 Machining toolbar

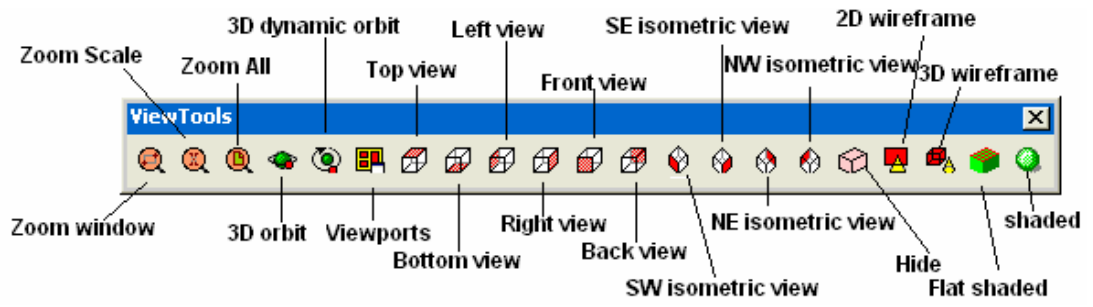


Figure J.11 View tools toolbar

VITA

Saleh Amaitik was born in Benghazi – Libya on Augustus 31, 1967. He received his B.Sc. degree in 1991 in Mechanical Engineering and M.Sc. in 1994 in Manufacturing Engineering from Garyounis University, Benghazi, Libya. He worked as a lecturer assistant in the Industrial Engineering Department of Garyounis University from 1994 to 1999. He has joined his Ph.D. Program in Mechanical Engineering Department of the Middle East Technical University in Feb. 2000. He has published one journal paper and about ten international conference papers. His main areas of research interest are Computer Aided Process Planning (CAPP), Feature-based Design, (FBD), Product data modeling using STEP, CAD/CAM integration, and Intelligent Manufacturing Systems (IMS).