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IPPS_R : a generative process planning system for rotational parts

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IPPS_R: A GENERATIVE PROCESS PLANNING SYSTEM FOR ROTATIONAL PARTS

by

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Abstract

IPPS_R: A Generative Process Planning System for Rotational Parts
Yijing Cai, Master of Applied Science in
Mechanical Engineering Department, Ryerson University, 2004

An automated machining process planning system for rotational parts is designed, developed and implemented. The system is called IPPS_R for Intelligent Process Planning System for Rotational parts. The IPPS_R system is designed for generating process plans for manufacturing rotational parts using metal cutting operations. A generative approach is employed to determine process operations and sequences automatically. For each machining feature, based on the accuracy and surface quality requirements, a fuzzy logic approach is developed to generate machining operations. A method of ranking the machining priorities of the features according to the feature relationship matrix is developed for sequencing operations. Moreover, the heuristic search of process plans is achieved by minimizing the number of setups in a plan. Finally, the IPPS_R system with a user-friendly interface is implemented in Microsoft Visual C++ on a personal computer, utilizing Microsoft Foundation Class (MFC). Two sample parts are used to demonstrate applications of the IPPS_R system.

Acknowledgement

I would like to express my special gratitude to my advisor, Dr. Liping Fang for his support, patience, encouragement and understanding throughout my graduate studies. His constant and invaluable guidance was essential to the completion of this thesis. I have the good fortune to be one of the students of him.

I would also like to acknowledge the rest of my thesis committee: Dr. Greg Kawall, Dr. Jeff Xi, and Dr. Saeed Zolfaghari for reading previous drafts of this thesis and providing many valuable comments that improved the contents of this thesis.

This thesis has been completed with time stolen from my son. Here, I wish to express my heartfelt thanks to my husband and my son for their continuous support and understanding.

Dedication

To my husband and my son

To my parents, my sisters and their families

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Glossary

Aggregation – The combination of the consequence of each rule in a fuzzy inference system in preparation for defuzzification.

Boring operations – Machining operations for enlarging an already drilled hole or irregular internal rotating shapes.

CAD (Computer Aided Design) – Computer packages are used to enter and analyze designs. These systems commonly use graphics to allow interactive definitions of geometries, and properties.

CAM (Computer Aided Manufacturing) – Computer packages are used to control, and drive manufacturing processes.

CAPP (Computer Aided Process Planning) – The process of converting a design to a process plan using computer software.

CIM (Computer-Integrated Manufacturing) – CIM is the increased integration of business and manufacturing functions through application of information technology; the use of computers in all aspects of manufacturing, with integration of functions and control in a hierarchy of computer systems.

CNC (Computer Numerical Control) – CNC allows the control of motion in an accurate and programmable manner through use of a dedicated computer within a numerical control unit, with a capability of local data input such that machine tools are freed from the need for "hard-wired" controllers.

Crisp Value – A precise numerical value such as 2, 5, or 7.34.

Cutting conditions – Cutting conditions refer the parameters adopted when chip removing is processed, such as cutting speed, cutting feed rate, cutting depth and cutting power.

Defuzzification – The process of transforming a fuzzy output of a fuzzy inference system into a crisp output.

Degree of membership – The output of a membership function, this value is always limited to between 0 and 1. Also known as a membership value or membership grade.

Drilling operations – Machining operations for producing small size holes.

Fuzzification – The process of generating membership values for a fuzzy variable using membership functions.

Fuzzy logic – A system of logic dealing with the concept of partial truth with values ranging between completely true and completely false.

Fuzzy set – A set where every element's degree of membership is specified by a value between 0 and 1. The elements have different degrees of belonging to the set.

Generative process planning – Process plans are created without reference to existing process plans.

GT (Group Technology) – Technique to classify parts and other elements by their form, functions or the processes by which they are manufactured. Also known as part classification.

Grinding operations – Machining operations used for manufacturing products with finest dimensional accuracy and surface finish. In grinding, material removal is achieved by employing a rotating abrasive wheel.

Honing operations – Machining operations for producing extremely high smooth holes.

Machining – In manufacturing, the term machining is used to cover all the chip-making processes, for instance, turning, milling, drilling, and boring.

Machining features – Pre-defined machining geometry such as pocket, slot, step, etc. These are used for determining machining methods in process planning.

Manufacturing – A series of interrelated of activities and operations that convert raw materials into designed products.

MAX Operation – The Maximum operation takes the greater of two values or the greatest of more than two values.

Membership function – A function that specifies the degree to which a given input belongs to a set or is related to a concept.

Milling operations – Machining operations for producing a variety of shapes such as flat, slot, and contoured surfaces.

MIN Operation – The Minimum operation takes the lesser of two values or the least of more than two values.

Modeling – The recreation of an event or object in a controlled environment in order to predict results from that event or object.

Operation sheet (Routing sheet) – A document used in manufacturing to indicate the sequence of operations, machines, or work centers that a part or product must follow.

Process planning – This term is used to refer to the selection of processes for the production of a part.

Reference Datum – A reference datum is a feature or group of features of a part, selected for use as a base from which other features or points are located within specified limits.

Scheduling – A final, detailed determination of the times employees will work, the sequence in which goods or services will be provided, and the operating times for machines.

Sequencing – A step in the scheduling process in which the ordering of jobs or work is determined.

Setup – The preparation of a machine to perform the required operations on a part.

Setup time – The time to get a machine ready to process a job.

STEP (Standard for Exchange of Product) – STEP is an international standard widely used for product data representation and exchange in manufacturing.

Surface Finish – Surface finish reflects the degree of surface quality. Usually, it is expressed by the average value of the surface roughness (*Ra*).

Tolerance –Tolerance of a feature (point, line, axis and surface) specifies the tolerance zone within which the feature is required to be contained.

TAD (Tool Approach Direction) – Tool approach is the direction of approach by the cutting tool when a component is processed.

Turning operations – Machining operations for producing cylindrical, taper, screw thread, or irregular surfaces on a rotating component.

Variant Process Planning – Process plans are developed by recalling previously created process plans for similar parts and allowing subsequent editing to resolve any differences. The important distinguishing feature is that the planner uses plans that are variations of other plans.

Chapter 1: Introduction

Today's competitive market needs enterprises to be innovative and agile. For many companies, it requires significant changes in the new product development process. It has also been demonstrated in many industries that time to market can play a critical role in a product's success or failure in today's competitive marketplace. Therefore, increasingly, time is a crucial factor in developing a new product. Design, material planning, process planning, scheduling, production, distribution and post-sale service are stages involved in developing and marketing a new product.

Two important activities contributing to a marketable and profitable product are design and manufacturing. Fundamental changes have taken place over the past three decades in both design and manufacturing areas (Chang et al., 1998). The design activity has been supported by computer-aided design (CAD) tools that enable the engineering drafting, surface and solid modeling, stress and heat flow analysis, vibration simulation, design optimization, and other sophisticated analyses. Meantime, computer-aided manufacturing (CAM) technologies allow easy production of complicated components and products. Process planning activity is used to convert a design into a list of operations and resources that are required by production activities, and computer-aided process planning (CAPP) is an important interface between CAD and CAM.

This chapter gives a brief introduction to design, manufacturing, process planning and automated process planning in the product development process. It also presents the objectives of the research and the organization of the thesis.

1.1 Design

Design is involved throughout the new product introduction process. Chang et al. (1998) summarizes the design process into five basic steps: (1) conceptual design, (2) design synthesis, (3) design analysis, (4) design evaluation, and (5) design representation.

An initial solution to a new product idea is usually rather aggregative, and it only contains the general concept of the product. The synthesis step adds more detail ideas to the initial concept. A draft geometrical shape of a product is formed and design dimensions are assigned to the product. During the first two steps, brainstorming should be applied to develop solutions to the problems. The analysis and evaluation steps focus on the best alternative from the views of functional requirements, cost and marketability of the product. Before the design is released for manufacturing, the final step of design representation should be applied. The design representation step is the detailed design phase. The detailed specifications of materials, geometric dimensions, tolerances, surface roughness, and special manufacturing requirements should be provided.

CAD technologies allow engineering designers to carry out 2D engineering drawing drafting, 3D wire frame design, 3D surface and solid modeling, assembly modeling, stresses and heat flow analysis, finite element analysis (FEA), vibration simulation, design optimization and other tasks efficiently and effectively. Implemented on personal computers (PCs), CAD packages have become very popular among industrial companies and individual users.

1.2 Manufacturing

Another important domain in the product development process is manufacturing. The terms manufacturing and manufacturing system have been widely used in both industry and academia (Armarego and Brown, 1969; Lee, 1999). However, the general definitions of the terms are still not standardized. In this thesis, several terms about manufacturing systems are defined as follows:

- *Manufacturing* is viewed as a series of interrelated activities and operations that convert raw materials into designed products. Those activities and operations include material planning, process planning, manufacturing system design, production, quality assurance, scheduling and control for manufacturing industries.
- *Manufacturing production* is a series of processes that are adopted to produce a product.

- *Manufacturing processes* are the manufacturing activities used to make products, such as turning, milling, drilling, boring and grinding.
- *Manufacturing system* is an organization that integrates all the interrelated activities of design, planning, manufacturing, control, financing, marketing and accounting.

The computer integrated manufacturing (CIM) system integrates CAD/CAM into one system. The development of CIM system has been a long process (Lee, 1999). With the increasing demand for more complex parts during the 1950s, numerical-control (NC) machines were invented. NC machines instead of skilled workers carried out complex tasks. The significant expansion of computer technology allows manufacturing to change dramatically. NC machines, robotics, computer-aided design (CAD), computer-aided manufacturing (CAM), and flexible manufacturing system (FMS) are widely used in manufacturing areas. These new technologies form a CIM system and enable enterprises to produce high quality and small-batch products at low cost.

In a CIM system, the design function has been assisted with CAD tools, and CAPP (computer-aided process planning) is a powerful link between CAD and CAM. In the following sections, the terms of process planning and automated process planning are discussed.

1.3 Process Planning

Process planning is used to determine detailed machining methods and sequences by which parts can be made from raw material, so it is a critical path between design and manufacturing. Generally, developing a process plan follows a procedure that consists of the following tasks (Huang et al., 1997; Chang and Chen 1998):

- *Part requirements analysis and machining features recognition.* The requirements of a part include information such as the part's material type and shape, geometrical sizes, tolerances and surface finish grades. The machining features are a collection of geometric elements such as a hole, a flat, a slot and a groove.

- *Selection of operations and machines:* Possible operations, such as turning, milling, drilling and grinding, and machines required for manufacturing a feature are determined.
- *Sequencing operations:* Possible sequences of operations to produce a part are developed.
- *Setup Planning:* Operations in a sequence are grouped in terms of setup requirements such as reference datum and select clamping method.
- *Selection of cutting conditions:* Cutting tool, removal depth, feed speed and machine spindle speed and so on are selected.
- *Calculation of production time.* The production time including both processing time and setup time for a sequence of operation is calculated.
- *Documentation of process sheet.* A process sheet is a list of instructions for processing – usually it includes the route, processes, process parameters, machine and tool selections, and setup method.

Usually, a process plan is made by an experienced human process planner based on the accumulation of experiences by himself and others. With the fast advances in computer technology, research on automated process planning systems has been progressing significantly in recent decades.

1.4 Automated Process Planning

Niebel (1966) proposed the first CAPP system. In his system, group technology (GT) is designed for various manufacturing processes. A crude process selection method was presented by Niebel based on the classification, material and size of a part. Due to the limitation of computer hardware and software, CAPP had not been feasible until the early 1980s (Zhang and Huang, 1994).

Early attempts to automate process planning focused on building computer-assisted systems for reporting, storage and retrieval of process plans (Chang, 1985). Such systems can efficiently reduce the routine tasks of a process planner. Recent research pursues development of automated process planning systems (Huang et al., 1994). These systems do not just carry out data storing and retrieving functions, but can also perform decision-making tasks. The development of such a system is more difficult and complicated.

Two approaches, namely variant and generative approaches, have been pursued in computer-aided process planning research (Cay and Chassapis, 1997). In the variant approach, standard process plans created manually by process planners are stored in a computer. By retrieving and modifying a standard plan taken from the database according to parts similarity, the planning system develops a process plan for a new component. In the generative approach, process plans are generated automatically for new components without referring to existing plans. Knowledge-based, rule-based and artificial intelligence-based reasoning techniques are applied in a generative process planning system. Comparied with traditional process planning, a CAPP system has the following advantages (Gu and Norrie, 1995):

- It can reduce the process planning time.
- It can reduce the skill requirement of a process planner.
- It can reduce the production cost due to efficient use of resources.
- It can reduce the man-made errors, creating more consistent plans.

1.5 Objective of the Research

In the CIM system, CAPP is the weakest link between CAD and CAM. Therefore, the main objective of this research is to develop an automated process planning system for rotational parts.

A generative approach is employed in developing the system. To achieve the overall objective, a number of specific research tasks are needed to be accomplished. The main tasks are:

- Determination of a part description method.
- Definition and application of specific rules to identify machining capabilities, to generate required operations, and to determine operation sequences.
- Heuristic search of operation sequences to generate a final process plan.
- Development of algorithms to implement specific rules and procedures.
- Implementation of the system in a suitable computing platform and software environment.
- Development of a user-friendly and interactive interface for the system.

1.6 Organization of the Thesis

This thesis is organized as follows: The first chapter contains an overview of design, manufacturing, process planning and automated process planning. In Chapter 2, a literature review on manufacturing processes, process planning, and computer-aided process planning is presented. Two major approaches in computer-aided process planning, the variant and generative methods, are discussed. An automated process planning system for rotational parts, the IPPS_R system, is developed in Chapter 3. The generative approach is employed in developing the IPPS_R system. In Chapter 4, the system implementation and user interface are demonstrated. Case studies and system verifications are presented in Chapter 5. The main contributions of this thesis are summarized in Chapter 6, along with some possible directions for future research.

Chapter 2: Manufacturing Process Planning

A perspective on manufacturing process planning methods and their related concepts is presented in this chapter. Moreover, a survey of the relevant literature on Computer-aided Process Planning (CAPP) as well as Artificial Intelligence (AI) techniques in CAPP is carried out. Since process planning deals with various activities, it embraces many sub-topics such as raw work-piece selection, operation selection, operation sequencing and set-up planning. Literature on each of these areas is presented one by one in the following sections.

2.1 What is Process Planning?

Products and their components are designed to carry out certain functions. Design specifications ensure these functions. Manufacturing activities transfer materials into designed components or products. A process plan (also called an operation sheet) is a list of instructions for producing the part. It usually contains the route, processes, process parameters, machine and tool selections, and setup methods (Chang et al., 1998), which is generally made by an experienced process engineer or planner. So process planning is an activity that transfers design specifications into manufacturing process details. To develop a process plan, a process planner has to have the following knowledge:

- Ability to interpret an engineering drawing.
- Familiarity with materials, machines, tools and machining methods.
- Ability to use manufacturing handbooks, to determine cutting parameters, and to compute process time and cost.

The development of process plans involves a number of activities. Based on the initial documents of a product, a flow chart to develop a process plan can be summarized as in Figure 2.1.

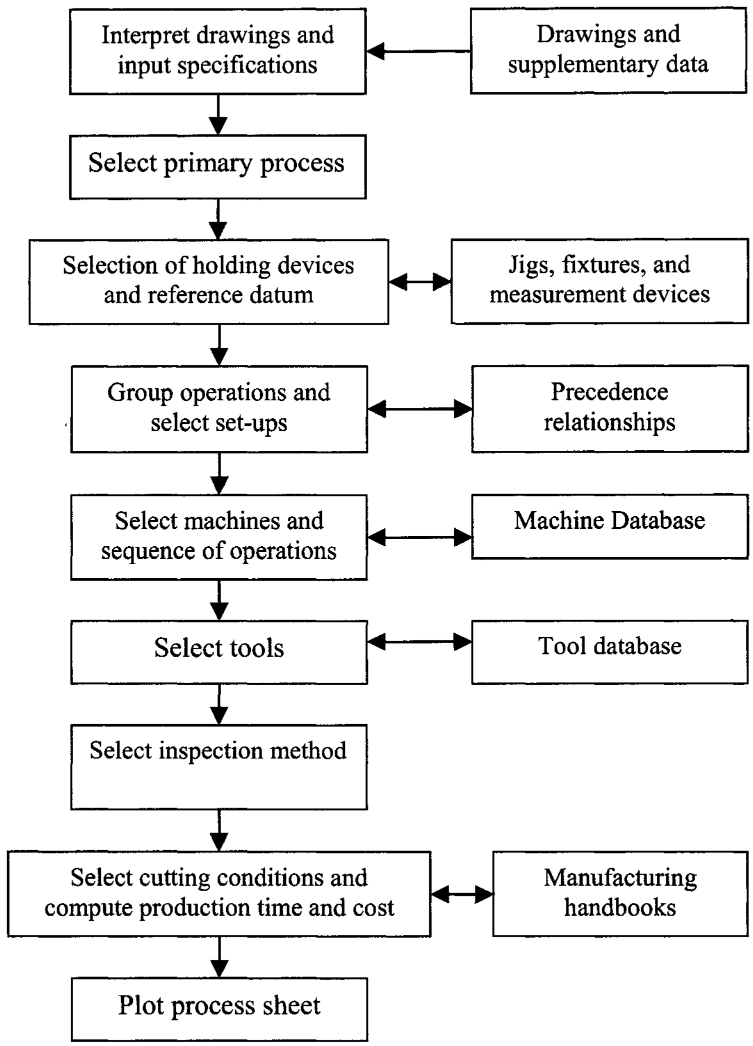
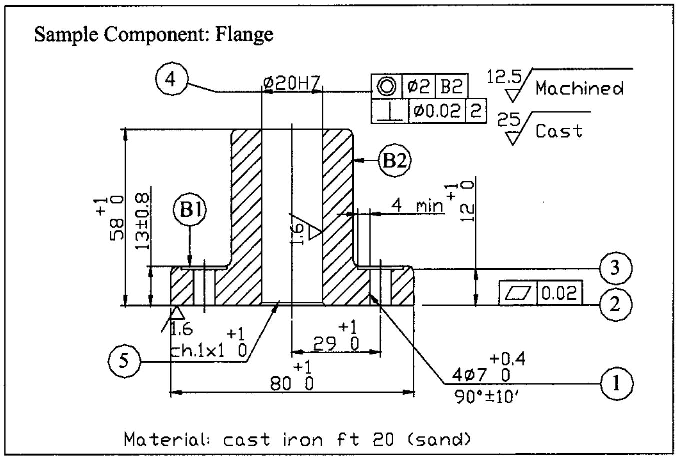


Figure 2.1. Flow Chart of Process Planning

2.2 Parts Recognition

Normally, designed products or components are described by the precise documents called the engineering drawings. Figure 2.2 is an example of an engineering drawing.



Source: Halevi and Weill (1995), Principles of Process Planning: A Logical Approach, pp.16-19, Chapman & Hall, London, U.K.

Figure 2.2. A Geometric Model Representing a Component

Process planning is used to interrupt those designed requirements from the engineering drawings and convert them into a series of operation instructions. In terms of engineering, the parts requirements can be defined as their machining features, dimensions and tolerance specifications. The terms related to process planning can be explained as follows:

- **Machining Features:** Features can be defined from different points of view, such as geometry, design, function, machining and assembly. From the aspect of machining, a feature is defined as a collection of related geometric elements that correspond to a particular manufacturing method or process. For example, rotational features correspond to operations in a lathe or a turning center, and prismatic features require operations in a miller or a machine center associated with 3D representation.

- **Size Tolerance:** Size tolerance is the difference between the maximum and minimum size limits of a geometric feature. The size tolerance tells how far different features can be from their desired size. For a precise feature, the deviation of size is only allowed within a tiny zone.

IT (International Tolerance) Grade Numbers specify the sizes of a tolerance zone. Preferred tolerance grades and parts basic sizes are listed in Table 2.1, and the relation between the basic size and its tolerance zone is shown in Figure 2.3.

Table 2.1. Tolerance Grades Table (Unit: mm)

Basic Size	Tolerance Grades					
	IT6	IT7	IT8	IT9	IT10	IT11
3	0.006	0.01	0.014	0.025	0.04	0.06
6	0.008	0.012	0.018	0.03	0.048	0.075
10	0.009	0.015	0.022	0.036	0.058	0.09
18	0.011	0.018	0.027	0.043	0.07	0.11
30	0.013	0.021	0.033	0.052	0.084	0.13
50	0.016	0.025	0.039	0.062	0.1	0.16
80	0.019	0.03	0.046	0.074	0.12	0.19
120	0.022	0.035	0.054	0.087	0.14	0.22
180	0.025	0.04	0.063	0.1	0.16	0.25
250	0.029	0.046	0.072	0.115	0.185	0.29
315	0.032	0.052	0.081	0.13	0.21	0.32
400	0.036	0.057	0.089	0.14	0.23	0.36

Source: Preferred Metric Limits and Fits (ANSI, 1978)

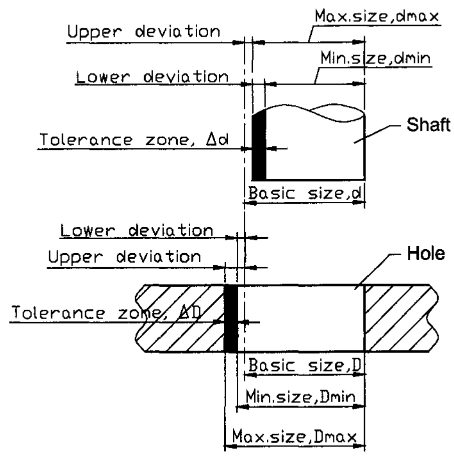


Figure 2.3. Basic Size and its Tolerance Zone
Source: Preferred Metric Limits and Fits (ANSI, 1978)

- **Positional Tolerance:** Positional tolerance is the specified volume in which the center point, axis, or center plane features of a part can vary from the theoretically exact position. A basic dimension is a number given to describe this true size, profile, orientation, or location of a feature, usually with respect to a datum (features from which other features can be compared) (Engineers Edge.com, 2003).

- **Surface Finish:** Surface finish reflects the degree of surface quality. Usually, it is expressed by the average value of the surface roughness (*Ra*). The equivalent table of the surface roughness values taken from ISO-1320 and their respective roughness grade numbers are shown in Table 2.2.

Table 2.2. Equivalent Surface Finish Table

Roughness values Ra (Micrometers)	Roughness values Ra (Micro-inches)	Roughness Grade Number	Equivalent Classes of Surface Quality *
50	2000	N12	1
25	1000	N11	2
12.5	500	N10	3
8.3	250	N9	4
3.2	125	N8	5
1.6	63	N7	6
0.8	32	N6	7
0.4	16	N5	8
0.2	8	N4	9
0.1	4	N3	10
0.05	2	N2	11
0.025	1	N1	12

Source: ISO (1992). Grade Number, ISO-1320:1992, http://www.predev.com/smg/specification.htm

* To simplify processing, the equivalent classes of surface quality are assumed in this thesis.

- **Tool Approach Direction (TAD):** Tool approach direction is the direction of approach by the cutting tool when a component is processed.

2.3 Overview of Operations

Machining processes are composed of a series of cutting activities (operations) executed on certain machine resources to transfer a raw material from its original shape to a desired product. In general, they are characterized by material removal actions. Turning, drilling, milling and grinding are typical machining operations. Detailed descriptions of these machining processes are shown in most manufacturing handbooks. Here is a brief description of machining operation applications to rotational parts, based on various manufacturing handbooks (Society of Manufacturing Engineers, 1976; Walsh, 1998).

- **Turning:** is a common machining process for producing cylindrical, taper, screw thread, or irregular surfaces on a rotating component. It is represented with the work-piece making rotational movements and the cutting tool making linear movements both parallel and towards to the rotating center.

- **Drilling:** is the operation for producing small size holes. It is characterized with the cutting tool making rotating movement about its axis and linear movement along its axis, but the work-piece keeping steady.

- **Reaming:** is a small sizing cutting operation used to make an already drilled hole more accurate in dimension and smoother in surface. The work-piece and cutting tool movements are the same as the drilling operation.

- **Boring:** is the operation for enlarging an already drilled hole or irregular internal rotating shapes. The cutting tool for boring is similar to that for turning, but the operation is shown as the work-piece keeping steady and the cutting tool making both rotating movement about its axis and linear movement along the axis.

- **Facing:** is the operation for finishing a small flat surface perpendicular to the rotating center.

- **Tapping:** is an operation for producing internal threads in work-pieces by using a threaded tool with multiple cutting teeth.

- **Milling:** is the process for producing a variety of shapes such as flat, slot, and contoured surfaces. In the milling process, the milling cutter, constituted with several cutting blades, involves rotating motion and the work-piece makes linear motion.

- **Grinding:** is the process used for manufacturing products with finest dimensional accuracy and surface finish. In grinding, material removal is achieved by employing a rotating abrasive wheel. Common grinding operations include surface grinding, cylindrical grinding, internal grinding, and center-less grinding. For rotational parts, the common used grinding operations are cylindrical grinding, internal grinding, and center-less grinding, where material removal is achieved by work-piece and grinding wheel making opposite rotations.

- **Honing:** is the operation for producing extremely high smooth holes. In a honing operation, only a tiny amount of material is removed. The tool makes rotating movement about its axis and linear movement along the axis, and the material of tool is similar to grinding wheel.

For rotational parts, most operations are implemented on lathes, CNC machining centers, external cylindrical grinders, internal cylindrical grinders and center-less grinding machines. Typical operations implemented on rotating work-pieces are summarized in Figures 2.4 to 2.6.

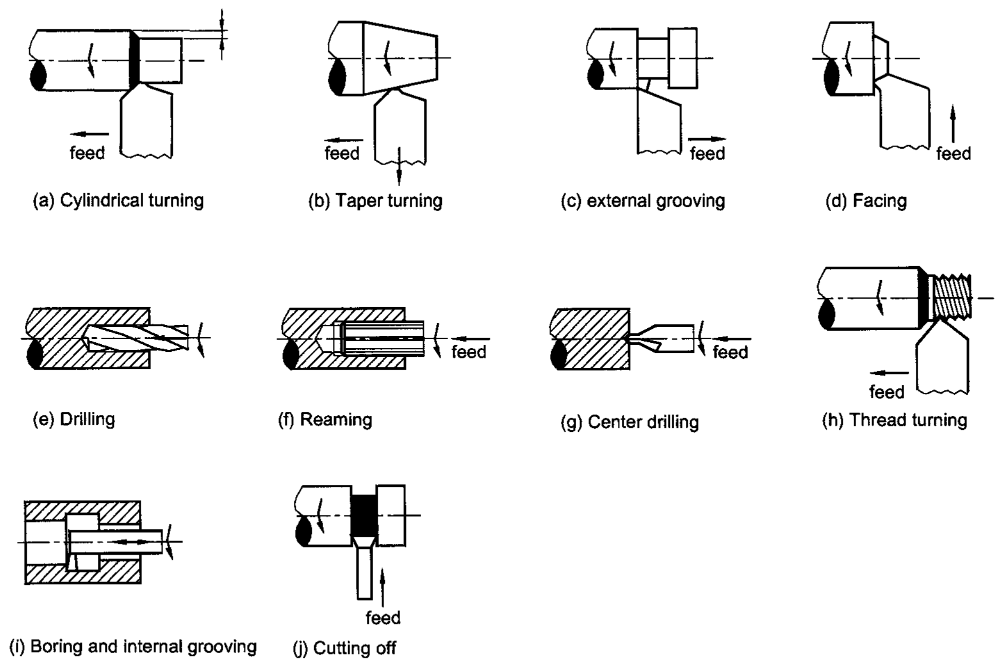


Figure 2.4. Various Cutting Operations Performed on Lathe

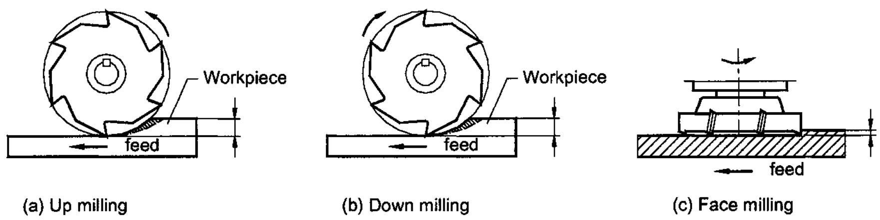


Figure 2.5. Milling Operations

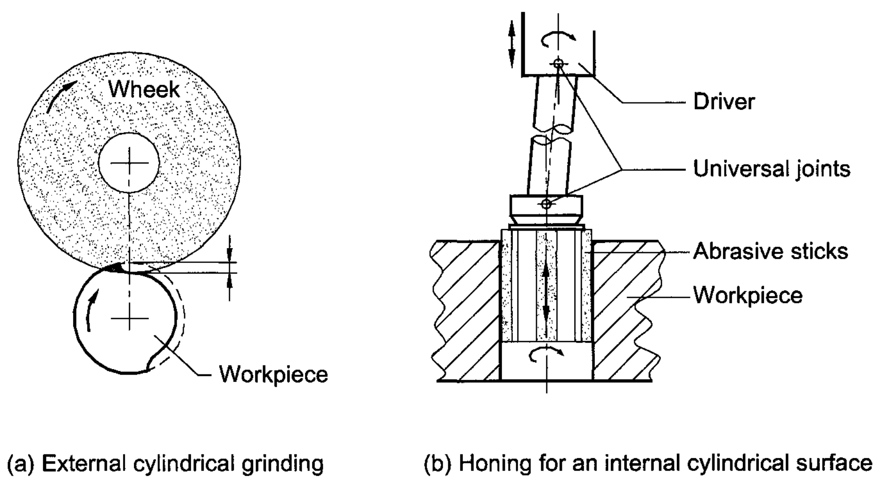


Figure 2.6. Grinding and Honing Operations

2.4 Experience-based Process Planning

Most process plans are developed based on experiences (Zhang, 1997). Experience comes from the accumulation of the knowledge of a process planner himself or others. Going through a long history of manufacturing development, that accumulated experience (that is, knowledge) is recorded and passed on from generation to generation. Typical information, such as process capabilities versus machining features, size tolerances or surface qualities, tool materials and shapes, tool life, work-piece materials and their respective cutting conditions, can be found in most manufacturing handbooks. For example, external rotational features can be generated by turning, a hole can be made by boring, drilling, reaming or honing, and flat surfaces can be formed by milling, shaping, broaching or surface grinding. Figure 2.7 illustrates the relationships between process capabilities and surface roughness values, and Table 2.3 shows the process capabilities and their respective accuracies and surface qualities.

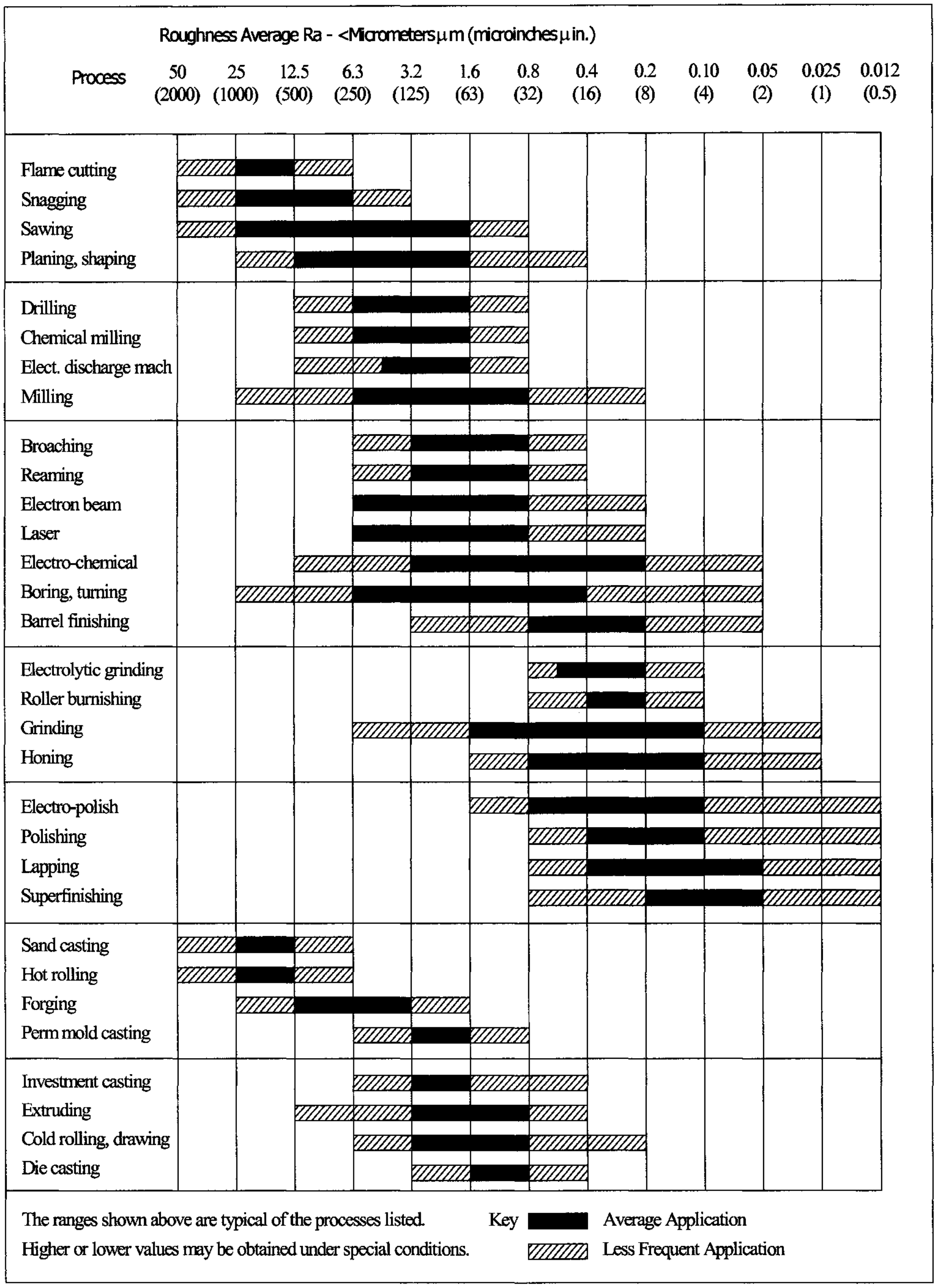


Figure 2.7. Surface Roughness Produced by Common Production Methods (ASME, 1995)

Source: Precision Devices, Inc., http://www.predev.com/smg

Table 2.3. Principles of Machining by Cutting, Abrasion, and Erosion

Machining method	Classes (according to ISO)																									
	Of accuracy												Of surface quality													
	1 to 3	4	5	6	7	8	9	10	11	12	13	14 to 16	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. CHIP REMOVING PROCESS																										
Turning				•	•	○	○	○	♦	♦	x	x	x	x	x	♦	○	○	•							
Boring				•	•	○	○	○	♦	♦	x	x	x	x	x	♦	○	○	•							
Drilling								•	○	♦	♦	x	x	x	♦	♦	○	•								
Reaming			•	•	○	○	♦	♦	x	x							x	♦	○	○	•	•				
Peripheral milling					•	•	○	○	♦	♦	x	x	x	x	♦	♦	○	○	•	•						
Face milling					•	•	○	○	♦	♦	x	x	x	x	♦	♦	○	○	•	•						
Planning & shaping						•	○	○	○	♦	♦	x	x	x	♦	♦	○	○	•	•						
Broaching			•	•	○	○	♦	♦	x	x	x	x				x	♦	○	○	•	•					
2. ABRASION PROCESSES A. Using abrasive tools																										
External cylindrical grinding			•	○	○	♦	♦	x	x								x	♦	♦	○	•	•				
Centre less cylindrical grinding			•	○	♦	♦	♦	x	x								x	♦	♦	○	○	•				
Internal grinding			•	○	○	♦	♦	x	x								x	♦	♦	○	•	•				
Surface grinding			•	○	○	♦	♦	♦	x	x							x	♦	♦	○	○	•				
Abrasive belt grinding				•	○	○	♦	♦	x	x						x	♦	♦	○	○	•					
Surface honing			•	•	○	♦	x	x									x	x	♦	♦	○	○	•			
Shaft and internal honing	•	•	•	○	○	♦	x											x	x	♦	♦	○	○	•		
Super finish	•	•	○	○	♦	♦	x												x	x	♦	○	○	•	•	
B. Using loose abrasive																										
Lapping		•	•	○	○	♦	♦	x									x	x	♦	○	○	•	•			
Mechanical polishing	•	•	○	○	♦	♦	x	x										x	x	♦	♦	○	○	•	•	
Vibratory & barrel finishing					•	•	•	○	○	♦	♦	x			x	x	♦	♦	○	•						
Abrasive-blast treatment				•	•	•	○	○	♦	♦	x	x			x	♦	♦	○	○	•	•					
Ultrasonic machining				•	•	○	○	♦	♦	x						x	♦	○	○	•	•					

Note:

Accuracy	Surface quality
x -- rough	x -- rough
♦ -- fairly accurate	♦ -- fairly smooth
○ -- accurate (mostly frequently used)	○ -- smooth (mostly frequently used)
• -- highly accurate	• -- extremely smooth

Source: Chang et al. (1998), Computer-Aided Manufacturing, *2nd Edition,* Prentice Hall, NJ, USA, pp.133, which in turn is based on Peregrinus Limited.

2.5 Computer-Aided Process Planning (CAPP)

Computer Integrated Manufacturing (CIM) system is a manufacturing system capable of meeting the requirement of developing new products. As a bridge of design and manufacturing, computer-aided process planning (CAPP) is essential to reduce the required time from product design to market. Early attempts to automate process planning focused on storage and retrieval of process plans. The storage and retrieval of process plans are based on part numbers. Such a system can reduce the routine work of a process planner. Recent research focuses more on the integrated CAD/CAM systems. Computer-aided process planning covers the issues from part representation, operation selection and sequencing, setup planning, tooling planning, optimizing cutting conditions to generating CNC codes. Rule-based, knowledge-based and artificial intelligence-based systems are reported in many publications.

There are two major methods in CAPP: the variant and generative methods (Chang and Wysk, 1985). The variant approach involves storing some typical process plans in a computer. A plan for a new part is formed by retrieving an existing plan for a similar part and making the necessary modifications to it. The generative approach involves generation of the new process plan for a part based on process knowledge and decision making rules. Recently, there has been significant interest in research that applies artificial intelligence approaches to automated process planning: applications of fuzzy logic, neural network and genetic algorithm in process selection, cutting condition selection and multi-level decision-making (Leondes, 2001; Zhao, 1995).

2.5.1 Variant Process Planning

The principle of the variant approach is based on Group Technology (GT) (Karadkar et al., 1996). GT is a classification method where similar parts are classified to one family group according to GT codes. Commonly used coding systems are Opitz, Miclass, KK-3, and Dclass systems (Chang and Wysk, 1985). In a variant system, several standard process plans are stored in a database, which are prepared manually by human process planners. To create a process plan for a new part, the part is first assigned a GT code. Next a standard process plan from a database is retrieved according to the GT code. Finally, the standard plan is modified to generate a plan for the new part. Currently, most existing commercial systems are variant-based process planning systems (Gu and Norrie, 1995).

The earliest typical variant systems are: CAPP, MULTICAPP, MIPLAN, MIAPP, MITURN, GENPLAN and PI-CAPP (Chang and Wysk, 1985). CAPP (CAM-I Automated Process Planning) (Link, 1976; Tulkoff, 1978), developed by the McDonnel Douglas Company, is a widely used commercial system for both rotational and prismatic parts, as well as sheet metal parts. Written in ANSI standard Fortran, it is a GT code-based variant system. The coding scheme for part classification and the output format needs to be developed by a user. A maximum 36-digit code is allowed. PI-CAPP (Planning Institute, Inc., 1980), developed by Planning Institute, Inc., has a built-in coding and classification system, which eliminates the requirement of a user-defined coding scheme.

2.5.2 Generative Process Planning

The next generation automated process planning systems are generative ones (Sadiaiah et al., 1998). A generative system does not store standard plans for parts planning. That is, generative systems are capable of developing process plans for parts not belonging to any existing part families. A generative process planning system has its own knowledge base that stores manufacturing data and rules that make decisions without user interaction. The generative approach is complex and a generative system is difficult to develop.

AUTAP (Automatistic Arbeits Planerstellumg) (Eversheim et al., 1980) is one of the most complete generative systems for both rotational parts and sheet metal parts (Chang and Wysk, 1985). It is able to deal with material selection, process selection, process sequencing, machine selection, tooling selection, clamping selection and part NC program generation. AUTOPLAN (Vogel and Adlard, 1981), developed by Metcut Research Associates, is based on a combination of variant and generative approaches. Process plans are retrieved according to GT codes; tooling layout, verification and work instruction preparation are done by graphical planning aids; tooling, cut and machine settings are determined by computer generation. Finally, process optimization is performed by minimum cost or maximum production rate. TIPPS (Total Integrated Process Planning System) (Chang and Wysk, 1983), developed at Purdue University, is a generative planning system integrating CAD with generative process planning. TIPPS has inputs from a CAD database in which a component is represented by a boundary model. It employs a local planning strategy where it creates a separate plan for each individual feature and then integrates the results together. This planning approach allows the system to be built easily. However, the final plan may not be efficient.

More recent generative systems deal with the features of a part globally. The information of a feature is not considered in isolation, but together with other features. Although such a system is much more difficult to build, the results have been improved significantly. Many papers on feature recognitions and representations have been published (Jasthi et al., 1995; Ming et al., 1998; Tseng and Joshi, 1998; Meeran and Taib, 1999). AMPP (Automated Process Planning System for Turned Parts) (Rogers et al., 1994) uses a CAD drawing as the initial input and then generates part input files for the process plan generator (CMPP) by utilizing translation software interpreting the CAD drawing. The CMPP is designed by variant and generative approaches, so it combines the merits of both of them. Finally, the process plan is translated into CNC codes through a translator called SmartCAM.

GISCAPP (Lau and Jiang, 1998) describes a methodology for the direct information transfer from CAD to CAPP without rewriting by any additional software. The ideal part description is extracted from a CAD database and then the output is delivered directly to the process planning system. It is difficult to implement this method in current research. GISCAPP contains a generic converter, a generic feature recognizer and a process planner. The CAD data are first converted to a STEP neutral file through a generic converter. Then a GT code is evolved from the STEP file through a feature recognizer. Finally, a process plan is generated through a process planner based on the GT code. STEP (Standard for Exchange of Product, ISO-10303) is an international standard widely used for product data representation and exchange in manufacturing (Bohn, 1996). In the GISCAPP system, a neutral format called STEP AP203 is adopted as an "agent" linking dissimilar computer systems. AP203 is a STEP application protocol for the exchange of 3D product data, which is a universally accepted format and supported by major CAD software, such as Pro/Engineer, CATIA, UNIGRAPHICS and CADD.

In comparison, variant systems are better developed and mature than generative systems. Variant systems are easy to build and suitable for planning processes of parts with great similarities (Cay and Chasspis, 1997). For planning processes of parts of great diversity, generative systems are much more suitable than variant systems. However, true generative systems are much more difficult to implement, although a lot of research has been carried out. Most CAPP systems in use now are either variant systems or semi-generative systems (combination of variant approach and generative approach).

2.6 Artificial Intelligence (AI) Techniques in CAPP

Artificial Intelligence (AI) techniques simulate human behavior in a computer, such as learning, reasoning, decision-making and so on. Currently, several AI techniques, such as Expert Systems (Wong and Siu, 1995; Younis and Wahab, 1997), Genetic Algorithms (Kayacan et al 1996; Dereli et al., 2001; Saravanan et al., 2003), Neural Network (Mei et al., 1995), and Fuzzy Logic (Zhang and Huang, 1994; Wang et al., 2001) have been utilized in CAPP.

2.6.1 Expert Systems

Process planning is a very complex task. The main difficulty in process planning is the huge amount of specialized factors that must be taken into account simultaneously: possible operations, available machines, machine capabilities, desired precisions, production costs, required technique supports, and so on. The process planner must develop a feasible plan from numerous possibilities. The complexities of process planning determine that only experienced process planners with specialized knowledge can carry out those tasks. An expert system is such a system that attempts to find a way to preserve the knowledge of human experts.

An expert system is also called a knowledge-based system that uses knowledge and reasoning techniques to solve problems. Expert systems differ from databases in that their knowledge is not simply retrieved as data, but can be used as the solutions for different types of problems. Huang and Zhang (1995) describe the expert system in terms of the following main components:

a) Knowledge base,
b) Knowledge acquisition mechanism,
c) A recognition/inference engine, and
d) A user interface.

The *knowledge base* is a file that contains the facts and heuristics made up by experts' knowledge. Manufacturing knowledge in a CAPP system is the part design knowledge (CAD module), the part process knowledge and the resource knowledge. It can be expressed as a computer code in the form of "if-then" rules, or forward and backward frames with a series of questions. The *knowledge acquisition mechanism* is used to acquire human expertise and transform it into the knowledge base. This module processes the data entered by the expert and transforms them into data understandable by the system. The *inference engine* is the knowledge processor that accesses the knowledge base and retrieves the rules to be executed. The *user interface* is designed to provide a convenient communication between the user and the inference engine. It enables a user to run the expert system, to input knowledge into the knowledge base, and to give a solution to the problem.

Expert systems have been widely developed in manufacturing areas (Chang, 1990; Badiru, 1992). Applications cover design, process planning, scheduling, material handling, production control and other activities.

2.6.2 Fuzzy Logic

Fuzzy logic is a technique for dealing with sources of imprecision and uncertainty. The foundation of fuzzy logic is fuzzy set theory (Zadeh, 1965). By mathematical means, fuzzy sets represent vagueness and imprecise information, hence the term fuzzy. The fuzzy logic was first introduced by Zadeh (1965). Since then, many theoretical developments have been made. Basically, fuzzy logic has been applied in areas where humans are required to make decisions, from control, design, and pattern recognition to process planning.

The basic idea of fuzzy logic simulates the human mind, where reasoning is usually approximate rather than exact. An exact rule cannot be defined for each possible problem. In these cases, the problems are described with approximate solutions. Fuzzy logic mimics this human logic using a mathematic model based on linguistic terms. Some examples of linguistic descriptions are "a few", "almost all", "good", "poor", "small", "medium", "large", "less or more important", etc. The use of fuzzy logic is simple. In fuzzy logic, system behavior can be described with a simple rule base containing many "if-then" statements. Therefore, the knowledge representation is explicit and the verification of the system performance is easy.

Zhang and Huang (1994) present a fuzzy approach to process plan selection when objectives are imprecise and conflicting. In their approach, each process plan is evaluated and its contribution to shop floor performance is calculated using the 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. The optimal process plan for each part is determined by the solution of a fuzzy integer-programming model. The consolidation procedure uses a dissimilarity criterion and selects a process plan that best utilizes manufacturing resources. The algorithm is demonstrated for a problem consisting of three parts and eight process plans. The algorithm is also tested against non-fuzzy algorithms found in the literature. In some circumstances, more reasonable solutions are achieved in manufacturing process planning.

Edvedžié and Pap (1999) introduced a model for linguistic evaluation of machine tool parameters, as well as a procedure for ranking alternatives of the parameters. Linguistic values quantity the machine tools' parameter values and their importance for given machining conditions, and then generate the suitable measurement for them. The ranking of alternatives is carried out in two stages. In the first stage, ranking is related to selection of linguistic values from a pre-defined dictionary according to the generated suitability measure. In the second stage, ranking includes evaluation of some additional parameters and experts' subjective belief about their importance for given conditions. The values of fuzzy set membership functions that represent appropriate linguistic variables are formed according to literature and empirical information as well as data and results of an experiment conducted in laboratory and real industrial environments.

2.6.3 Breadth-First Search Technique

The breadth-first search method is an AI technique. This method is applied to search a solution in tree-structured problems. The initial state of the problem is the first node of the structure; the second level nodes display all the possible solutions coming from the initial state. Successively, new levels are established and new states are added into the tree until a final solution is found. The graphic representation of the breadth-first search method is shown in Figure 2.8. The breadth-first search method searches all the possible solutions, so it can certainly find a best solution for a problem.

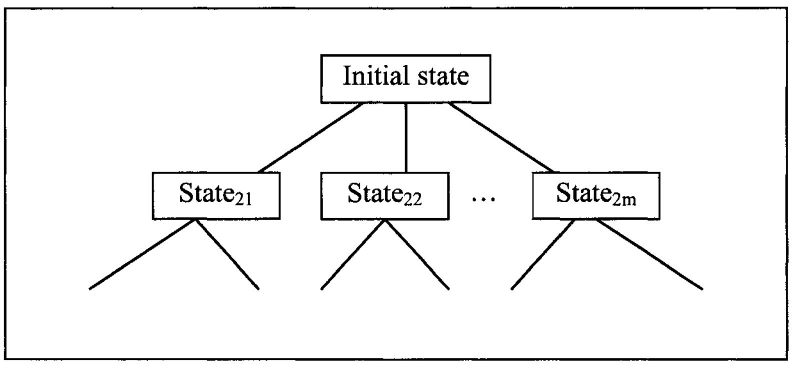


Figure 2.8. Graphic Representation of the Breadth-First Search Method

2.7 Optimization Techniques in CAPP

Some research on optimization of process planning in CAPP has been reported in the literature. Ahmad et al. (2001) summarize optimum process plan problems as a time-based or cost-based method or the combination of these two. The most frequent uses of optimization areas are tool selection, process selection, set-up selection and cutting condition selection.

Dereli et al. (1999) introduce the application of a genetic algorithm for determination of the optimal sequence of machining operations based on either minimum tool change or minimum tool traveling distance or safety. Combination of these criteria also might be used. The optimum position of tools on the automatic tool changer or turret magazine of a CNC machine tool by using a genetic algorithm is also explained. Chang and Chen (1995) illustrate a self-organizing fuzzy-net optimization system to generate a knowledge bank that can show the required cutting power for a short length of time in an online NC milling machine, where a fuzzification module and a defuzzification module are implemented to perform the procedure.

It is worth pointing out that there is no optimum solution in reality about process planning. Process planning is based on accumulated knowledge that cannot be described with precise mathematical models. The optimization result is only a heuristic solution for a process plan.

Chapter 3: Development of a Process Planning System for Rotational Parts

3.1 Overview

The main objective of this thesis is to develop an automated process planning system for rotational parts. Manufacturing parts can be classified into two large families – rotational parts or non-rotational parts. For a rotational part, its geometric shape is symmetric about center axis. That is, the geometric shape is formed through a line or a curve rotating around a centerline. A large proportion of parts in machining manufacturing belong to rotational parts. Thus, research on automated process planning for rotational parts has significant meaning in manufacturing.

The proposed system named **IPPS_R** (Intelligent Process Planning System for Rotational parts) is an automated process planning system by generative approach. Developed in the Microsoft Visual C++ environment, it is capable of installation and operation in the Windows environment on a personal computer (PC). The development of the proposed automated process planning system is composed of the following steps:

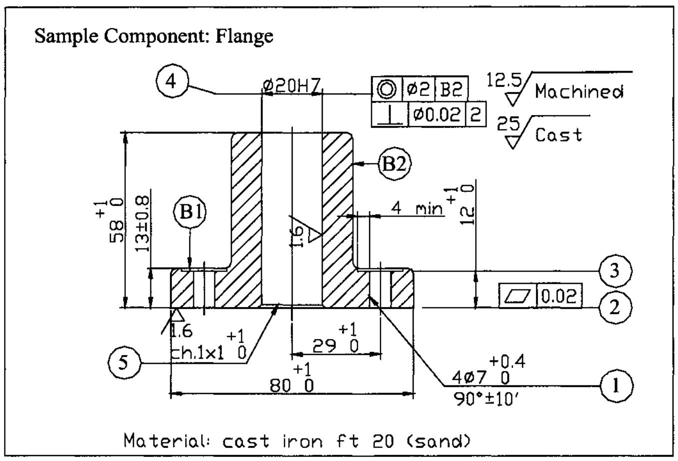
- Representation of parts.
- Generation and selection of operations.
- Selection of machines.
- Generation of preliminary operation sequences.
- Selection of setups.
- Heuristic search of operation sequences at the process level.

The proposed automated machining process planning system focuses on developing modules for generation and selection of operations, operation sequencing, selection of set-ups, and heuristic search of operation sequences automatically. In the first part of this chapter, methodologies for the representation of parts, generation and selection of operations, generation of preliminary process plan, selection of setups, and heuristic search of operation sequences are discussed. The IPPS_R system is described in the second part.

3.2 Representation of Parts

3.2.1 Part Representation

A part can be precisely represented by a CAD drawing and stored. Figure 3.1 illustrates an example of a part drawing, where the geometric shape, dimensions, desired surface quality and accuracy, as well as material are represented with symbolic expression and text description.



Source: Halevi and Weill (1995), Principles of Process Planning: A Logical Approach, pp.16-19, Chapman & Hall, London, U.K.

Figure 3.1. Flange

Ideally, part information required by an automated process planning system should be able to be directly retrieved from the CAD data. However, it is difficult to realize this function currently due to the limitation of computer hardware and software. A number of research projects about automated feature recognition have been carried out, as discussed in the previous chapter. Currently a proposed method is to convert CAD data into a universal data exchange format that is accepted by most of dissimilar systems, and then required part information is extracted from the data exchange file through a feature recognizer (a special-developed software) by applying certain algorithms (Subrahmanyam and Wozny, 1995; Zhou et al., 2002). The development of such a system is quite complicated and many attempts are only limited for parts within a small portion of the geometric shapes.

The **IPPS_R** system does not focus on development of automatic feature recognition model. An existing coding system called Opitz system is employed for part representation and a number of dialog boxes are designed to obtain manufacturing feature information.

3.2.2 Part Representation by the Opitz Coding System

3.2.2.1 The Opitz Coding System

Parts coding systems come from group technology (GT), where parts are grouped into families according to their GT codes. Similar parts belong to one family and require similar operations.

The Opitz coding system (Opitz, 1970), developed at the Aachen University of Technology in Germany, is one of the best-known coding systems for part representation. The Opitz code consists of a 5-digit geometric code and a 4-digit supplementary code. The first five decimal digits represent the geometric properties of a part and the remaining four decimal digits describe the major dimension, material type, material form, and accuracy of a part. A dimension ratio is used in classifying part classes: the length/diameter ratio is used to classify rotational components, and length/width and length/height ratios are used to classify non-rotational components. The structure of Opitz code is summarized in Figure 3.2, and the complete Opitz classification system is given in Appendix A.

Digit	Part Code
1	Part class (0-9)
2	External shape (0-9)
3	Internal shape (0-9)
4	Plane surface machining (0-9)
5	Auxiliary holes (0-9)
6	Dimension (0-9)
7	Material (0-9)
8	Initial form of material (0-9)
9	Accuracy in coding digit (0-9)

Figure 3.2. The Structure of Opitz Code
Source: Opitz (1970). *A Classification System to Describe Workpieces*, Pergamon Press, Elmsford, New York

3.2.2.2 Part Code Generation

The IPPS_R system uses the Opitz code to represent rotational parts. To reduce the complication of system modeling, the effort involved is limited to the manufacturing of rotational parts (exclusive of gear) using metal cutting operations. Only those parts listed in Table 3.1 can be handled by the system. Detailed information about part representation are described as follows:

- 1st digit of the code C_1 –part class:

  $C_1=0\text{-}2$, a part belongs to rotational part families
  Let L_{max} be the overall length of a rotational part,
  D_{max} be the maximum diameter of a rotational part,
  R be the ratio of the length over diameter,
  $R=L_{max}/D_{max}$
  If $(R \leq 0.5)$ *then* $C_1=0$ *(plate family)*
  If $(0.5 < R < 3)$ *then* $C_1=1$ *(rotating body)*
  If $(R \geq 3)$ *then* $C_1=2$ *(shaft family)*

- 2nd digit of the code C_2 – external shape of a part:

  $C_2=0$ *when the part is smooth without shape elements*
  $C_2=1$ *when the part steps to one end without shape elements*
  $C_2=2$ *when the part steps to one end with screw thread*
  $C_2=3$ *when the part steps to one end with functional groove*
  $C_2=4$ *when the part steps to both ends without shape elements*
  $C_2=5$ *when the part steps to both ends with screw thread*
  $C_2=6$ *when the part steps to both ends with functional grove*
  $C_2=7$ *when the part steps to both ends with functional taper*

- 3rd digit of the code C_3 – the internal shape of a part:

  $C_3=0$ *when the part is smooth without shape elements*
  $C_3=1$ *when the part steps to one end without shape elements*
  $C_3=2$ *when the part steps to one end with screw thread*
  $C_3=3$ *when the part steps to one end with functional groove*

C_3 =4 when the part steps to both ends without shape elements

C_3 =5 when the part steps to both ends with screw thread

C_3 =6 when the part steps to both ends with functional grove

C_3 =7 when the part steps to both ends with functional taper

- 4th digit of the code C_4 – with plane surface machining:

C_4=0 when the part has no plane surface to be machined

C_4=1 when the part has external plane surfaces in one direction

C_4=2 when the part has external plane surfaces related to one another by graduation around a circle

C_4=3 when the part has external groves and/or slots

C_4=5 when the part has external plane surfaces and/or grooves and/or slots

C4=6 when the part has internal grooves and/or slots

C4=8 when the part has both external and internal grooves or slots

- 5th digit of the code C_5 – part auxiliary holes:

C_5=0 when the part has no auxiliary holes

C_5=2 when the part has axial holes related by a drilling pattern

- 6th digit of the code C_6 – part maximum dimension:

Let $A=max(D_{max}, L_{max})$

C_6=0 when $A \leq 20$

C_6=1 when $20 < A \leq 50$

C_6=2 when $50 < A \leq 100$

C_6=3 when $100 < A \leq 160$

C_6=4 when $160 < A \leq 250$

C_6=5 when $250 < A \leq 400$

- 7th digit of the code C_7 – part material:

C_7=0 when the part is made of cast iron

C_7=3 when the part is made of low carbon steel without heat treatment

C_7=4 when the part is made of carbon steel with heat treatment

C_7=5 when the part is made of alloy steel without heat treatment

C_7=6 when the part is made of alloy steel with heat treatment

- 8th digit of the code C_8 – part material shape:

C_8=0 when the part is a black round bar
C_8=1 when the part is a bright drawn round bar
C_8=2 when the part is a tube
C_8=7 when the part is a cast or a forged component

- 9th digit of the code C_9 – part accuracy:

C_9=0 when accuracy is not specified
C_9=1 when the tolerance grade is 5 (ISO standard)
C_9=2 when the tolerance grade is 6 (ISO standard)
C_9=3 when the tolerance grade is 7 (ISO standard)
C_9=4 when the tolerance grade is 8 (ISO standard)
C_9=5 when the tolerance grade is 9 (ISO standard)
C_9=6 when the tolerance grade is 10 (ISO standard)

Table 3.1. Opitz Coding System for Rotational Parts Implemented in the IPPS_R System

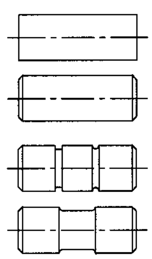
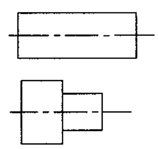
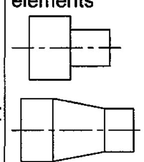
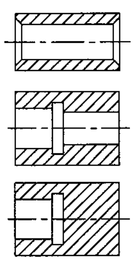
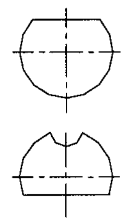
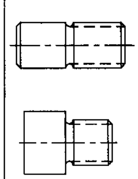
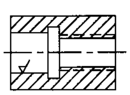
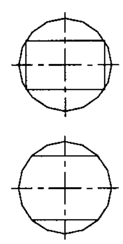
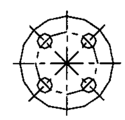
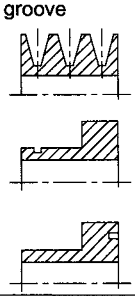
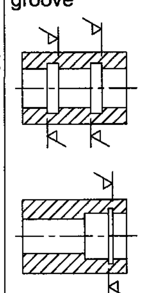
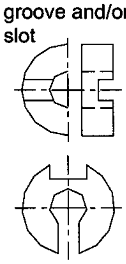
GEOMETRICAL CODE FOR RATIONAL PART WITHOUT DEVIATION					
Code	1st Digit Component Class	2nd Digit External shape, external shape elements	3rd Digit Internal shape, internal shape elements	4th Digit Plane Surface Machining	5th Digit Auxiliary holes, Gear Teeth, Forming
0	L/D <= 0.5	Smooth, no shape elements 	without through bore, without blind bore 	no surface machining	no gear teeth: no auxiliary hole(s)
1	0.5<L/D<3	Stepped to one end: no shape elements 	Stepped to one end: no shape elements 	external plane surface and.or surface curved in one direction 	
2	L/D >= 3	Stepped to one end: with screwthread 	Stepped to one end: with screwthread 	external plane surfaces related to one another by graduation around a circle 	no gear teeth: holes related by a drilling pattern 
3		Stepped to one end: with functional groove 	Stepped to one end: with functional groove 	External groove and/or slot 	
3 to 9	non-rotating parts				

Table 3.1(cont'd). Opitz Coding System for Rotational Parts Implemented in the IPPS_R System

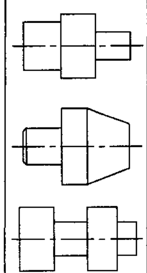
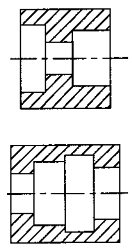
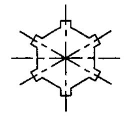
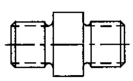
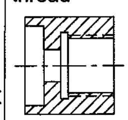
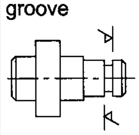
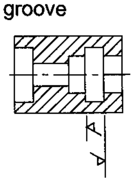
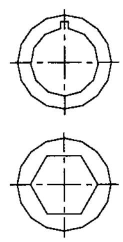
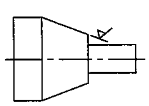
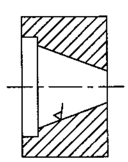
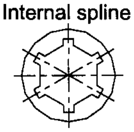
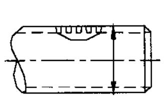
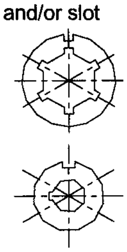
GEOMETRICAL CODE FOR RATIONAL PART WITHOUT DEVIATION								
1st Digit Component Class		2nd Digit External shape, external shape elements		3rd Digit Internal shape, internal shape elements		4th Digit Plane Surface Machining		5th Digit Auxiliary holes, Gear Teeth, Forming
0	L/D <= 0.5	4	Stepped to both ends (multiple increases): no shape elements 	4	Stepped to both ends (multiple increases): no shape elements 	4	External spline 	
1	0.5<L/D<3	5	Stepped to both ends (multiple increases): with screw thread 	5	Stepped to both ends (multiple increases): with screw thread 	5	External plane surface and/or groove and/or slot	
2	L/D >= 3	6	Stepped to both ends (multiple increases): with functional groove 	6	Stepped to both ends (multiple increases): with functional groove 	6	internal plane surface and/or groove 	
3 to 9	non-rotating parts	7	functional taper 	7	functional taper 	7	Internal spline 	
		8	operating thread 			8	External & internal spline and/or groove and/or slot 	

Table 3.1(cont'd). Opitz Coding System for Rotational Parts Implemented in the IPPS_R System

SUPPLEMENTARY CODE							
6th Digit Diameter 'D' or Edge length 'A'		7th Digit Material		8th Digit Initial form of materials		9th Digit Accuracy in coding digit	
0	<=20	0	Cast Iron	0	Round bar, black	0	No accuracy specified
1	>20<=50	2	Steel<=26.5 ton/in^2 Not heat treated	1	Round bar, bright drawn	1	2
2	>50<=100	3	Steel > 26.5 ton/in^2 Heat treatable low carbon & cast hardening steel, not heat treated	2	Tubing	2	3
3	>100<=160	4	Steels 2 & 3 Heat treated	6	Plate and Slabs	3	4
4	>160<=250	5	Alloy stell Not heat treated	7	Cast or forged components	4	5
5	>250<=400	6	Alloy stell Heat treated	9	Pre-machined components	5	2 and 3
		9	Other materials			6	2 and 4
						7	2 and 5
						8	3 and 4
						9	(2+3+4+5)

Source: Opitz (1970), *A Classification System to Describe Workpieces,* Pergamon Press, Elmsford, New York

3.2.3 Feature-based Representation

3.2.3.1 Machining Features

From the viewpoint of manufacturing, a part can be described by several machining features that require certain operations. A specific feature corresponds to one or several machining operations. Although the Opitz system provides an effective way to describe the properties of a part, it does not provide enough information for producing a generative process plan. The proposed system adopts the type, size, tolerance, surface finish and tool access approach of a feature, as well as operation precedence between features to provide further descriptions for rotational parts.

- **Feature types**: The proposed system can deal with 15 machining features which are commonly found in rotational parts: (i) External cylinder, (ii) External tapered feature, (iii) External thread, (iv) External plane perpendicular to axis, (v) External plane parallel to axis, (vi) External slot, (vii) External groove, (viii) Internal cylinder, (ix) Internal tapered feature, (x) Chamfer, (xi) Internal thread, (xii) Internal groove, (xiii) Center hole, (xiv) Auxiliary holes, and (xv) Counter sink. Parts with features beyond the above ones cannot be processed by the system.

- **Feature's sizes:** A feature's size is characterized by its diameter, length, width, depth, or angle.

- **Feature's size tolerance:** International tolerance (IT) grade numbers are employed to indicate size accuracies. For a certain size, an IT number corresponds a tolerance zone (see Table 2.1).

- **Feature's surface finish:** Roughness classes are used to express surface qualities. Each roughness class has a respective roughness value (*Ra*) (see Table 2.2).

- **Feature's tool approach direction:** The proposed system employs the following notation (Huang and Zhang, 1996) for the tool approach directions:

$$A_i = \begin{cases} 1, & \text{if feature } i \text{ can only be machined from the left} \\ 2, & \text{if feature } i \text{ can only be machined from the right} \\ 3, & \text{otherwise} \end{cases}$$

where: i – feature index,
A_i – tool approach direction for feature i, $i=1$ to N_m, and
N_m – total number of features to be machined.

- **Precedent feature:** Let N_m denote the total number of the features of a component to be machined and, i and j two individual features. If the final status of feature j (F_j) can only be formed after the final status of feature i (F_i) is formed, then F_i is called a precedent feature of F_j. The relationships among the features of a component can be observed from its geometric model. For the flange component shown in Figure 3.1, the precedent relationships among the features of the flange can be summarized as given in Table 3.2.

Table 3.2. Feature Precedent Relationships of the Flange

Feature i	Precedent Features
1	F_4
2	B_1^*
3	F_1, F_4
4	B_2^*, F_2, F_5
5	F_2

* Features B_1 and B_2 are non-machined ones.

3.2.3.2 Feature Relationship Matrix

Based on the precedent features, a feature relationship matrix, denoted by *RS*, can be defined. Define the *ij* element of the feature relationship matrix *RS* as:

$$RS_{ij} = \begin{cases} 1, & \text{If feature } F_j \text{ is a precedent feature of } F_i \\ 0, & \text{otherwise} \end{cases}$$

where $i = 1,2,\ldots,N_m$, and $j = 1,2,\ldots,N_m$

For the Flange shown in Figure 3.1, the feature relationship matrix *RS is*

	F1	*F2*	*F3*	*F4*	*F5*
F1	*0*	*0*	*0*	*1*	*0*
F2	*0*	*0*	*0*	*0*	*0*
F3	*1*	*0*	*0*	*1*	*0*
F4	*0*	*1*	*0*	*0*	*1*
F5	*0*	*1*	*0*	*0*	*0*

The feature relationships of the Flange shown in Figure 3.1 can be displayed graphically as give in Figure 3.3, where individual features are represented by the nodes of a graph and the priority relationship of two features is expressed as a directional arc.

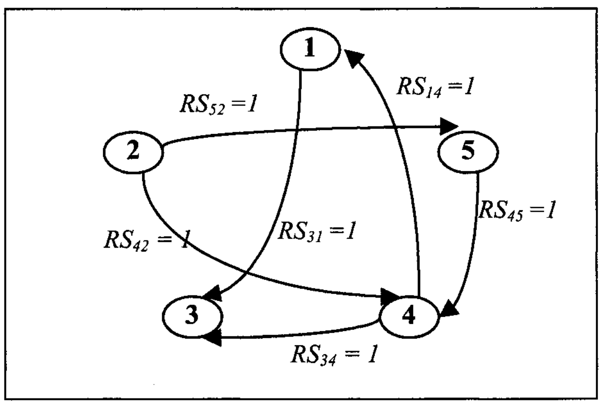


Figure 3.3. Graphical Representation of the Feature Relationships for the Flange

3.3 Generation and Selection of Operations by Fuzzy Logic Approach

An automated operation generation and selection model based on fuzzy approach is developed for the IPPS_R system. In this approach, pre-defined fuzzy membership functions on machining features and fuzzy operation selection rules are built into the system. When the type and size of a feature are given, the membership functions on the feature are generated.

Operations for each individual feature are selected through evaluating and aggregating the results of membership functions according to its tolerance and surface roughness requirements. Fuzzy set, fuzzy logic, fuzzy membership functions and fuzzy operation selection rules are discussed in this section.

To simplify the development of an automated process planning system, it is assumed that a single operation can only be implemented on a certain machine. Information on operations and their respective machines are pre-stored in the system.

3.3.1 Fuzzy Approach

3.3.1.1 Fuzzy Set Theory

Fuzzy set theory, first introduced by Zadeh (1965) to deal with problems that are hard to define exactly, has been used extensively as a modeling tool for complex systems. The principal concept of fuzzy set theory is the concept of fuzzy set. Contrary to the classical notion of a set, the boundary of a fuzzy set is not required to be precise. That is, membership in a fuzzy set is not a matter of affirmation or denial, but a matter of degree (Klir and Yuan, 1985). By mathematical means, fuzzy sets represent vague, imprecise and uncertain information, hence the term fuzzy. Some examples of linguistic descriptions are a few, almost all, good, poor, small, medium, large, less or more important, etc. A fuzzy set can be described using following mathematical expressions (Pedrycz and Gomide, 1998):

A collection of objects (a domain, space or universe of discourse) X has a fuzzy set A described by a membership function μ_A that maps each element of X into numbers in [0,1], $\mu_A: X \rightarrow [0, 1]$. Thus, a fuzzy set A in X may be represented as a set of ordered pairs of a generic element $x \in X$ and its grade of membership: $A = \{(\mu_A(x)/x)|x \in X\}$. $\mu_A(x)$ takes the values in the interval [0,1].

Fuzzy sets can be defined in either finite or infinite universes using different notations. For instance, if a universe X is discrete and finite, $X = \{x_1, x_2, ..., x_n\}$, then the fuzzy set A = $\{(a_i/x_i)|\ x_i \in X\}$, where $a_i = \mu_A(x_i)$, $i=1,2,...,n$, may be denoted by (Zadeh 1965)

$$A = a_1/x_1 + a_2/x_2 + \ldots + a_n/x_n = \sum_{i=1}^{n} a_i/x_i$$

In this notation, the sum should not be confused with the standard algebraic summation. The only purpose of the summation symbol in the above expression is to denote the set of ordered pairs. When there exists only one point x in a universe for which the membership degree is non-null, it is denoted by $A = \{a/x\}$.

3.3.1.2 Fuzzy Logic

Fuzzy logic is a technique for dealing with sources of imprecision and uncertainty. It has two meanings. The first meaning is multi-valued or "vague" logic. Everything is a matter of degree including truth and set membership. The second meaning is reasoning with fuzzy sets or with sets of fuzzy rules (Kosko, 1994). The foundation of fuzzy logic is fuzzy set theory. In many cases, an exact rule or law cannot be defined for each possible problem. Humans develop approximated solutions to uncertain or imprecise problems. By mimicking human's approximate logic, fuzzy logic incorporates a simple, rule-based approach (e.g., IF-THEN rules) to solve a decision making problem rather than to model a system mathematically. A fuzzy logic model is empirical-based, relying on an operator's experience rather than his/her technical understanding of the system.

Fuzzy logic has been proven to be an efficient tool for many control system and decision making applications since it mimics human approximated reasoning. Applications of fuzzy logic have been reported in many fields, from controls, to engineering design, process planning, operation research, robotics, and pattern recognition. It uses an imprecise but very descriptive language to deal with input data, more like a human operator. It is very robust and often used in the situations where problems have no exact solutions.

3.3.1.3 Approach to Solving a Fuzzy System

Computers are precise computing machines. Unlike humans, they require crisp inputs and crisp outputs. The fuzzy interface system maps input data into output data using fuzzy rules. Generally, a fuzzy system can be broken down into five individual steps:

- **Fuzzification** - this is used to take the crisp inputs and apply the membership functions to determine the degree of certainty to which they belong to the appropriate fuzzy sets.

- **Fuzzy Operators** - as there are sometimes many fuzzy sets, this is the application of fuzzy logic operators on the sets.

- **Fuzzy Rules** - this is the application of fuzzy rules to each of the sets.

- **Aggregation** - (summation) as often many fuzzy sets are used in a system, the fuzzy sets must be combined to yield a single output fuzzy set.

- **Defuzzification** - This is to apply one of the several methods to convert the final single output fuzzy set to a crisp number.

3.3.2 Operation Selection

3.3.2.1 General Method to Build Fuzzy Sets and their Membership Functions

The process capabilities and their respective machining accuracies and surface qualities are given in Table 2.3. These principles came from the accumulation of manufacturing practices. For a machining feature with a certain accuracy and surface quality requirement, there are multiple choices of operations with different process capabilities. In a real manufacturing environment, the process planning problem is solved by an experienced process planner based on his experience. Hence, uncertain and imprecise factors affect the decision making of the process planner.

Proposed operation selection model is designed as a fuzzy system. The crisp inputs are assumed to be a specific accuracy class x_1 and a specific surface quality class x_2 of a feature. The crisp output y is the desired operations for a feature. The fuzzy logic structure of the system is expressed in Figure 3.4.

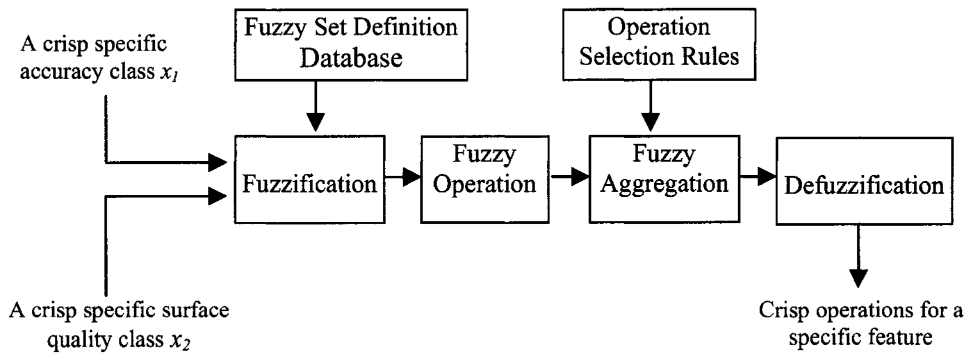


Figure 3.4. Fuzzy Logic of the IPPS_R System

Based on the process capability information provided in Table 2.3, fuzzy sets and their membership functions for selection of operations can be constructed. The general method to construct fuzzy sets and fuzzy membership functions is developed as follows:

Let *IT* be an operation tolerance set defined on an accuracy class domain X_1. Then, for each element x_1 of X_1, the symbol $\mu_{IT}(x_1)$ denotes the degree of x_1 in *IT*. Typically, fuzzy set *IT* is expressed as ordered pairs:

$$IT = \{(\mu_{IT}(x_1)/x_1) \mid x_1 \in X_1\}.$$

Similarly, let *IS* be an operation surface finish set defined on a domain space X_2 (surface quality class). Then, for each element x_2 of X_2, the degree of x_2 belongs to *IS* can be expressed as membership function $\mu_{IS}(x_2)$. Fuzzy set *IS* is expressed as ordered pairs:

$$IS = \{(\mu_{IS}(x_2)/x_2) \mid x_2 \in X_2\}.$$

3.3.2.2 Proposed Fuzzy Operation Selection Approach

The proposed fuzzy operation selection approach is presented. Linguistic variables, fuzzy sets and fuzzy membership functions are defined in this section.

3.3.2.2.1 Fuzzy Operation Sets on Linguistic Variables

Based on the process capability information provided in Table 2.3, linguistic variables, fuzzy sets and universal sets for the operation selection of the IPPS_R system are defined as shown in Table 3.3.

Table 3.3. Definition of Linguistic Variables, Fuzzy Sets, and Universal Sets

Linguistic Variables	Fuzzy Sets	Universal Sets
Tolerance *{IT}*	*TT* – Turning tolerance *BT* – Boring tolerance *EGT* – External grinding tolerance *IGT* – Internal grinding tolerance *MT* – Milling tolerance *DRT* – Drilling tolerance *RT* – Reaming tolerance *HT* – Honing tolerance *SFT* – Super-finishing tolerance	X_1 – Accuracy class domain
Surface quality *{IS}*	*TS* – Turning surface quality *BS* – Boring surface quality *EGS* – External grinding surface quality *IGS* – Internal grinding surface quality *MS* – Milling surface quality *DRS* – Drilling surface quality *RS* – Reaming surface quality *HS* – Honing surface quality *SFS* – surface quality set by Super-finishing	X_2 – Surface quality class domain
Machining Operation *{OP}*	*T* – Turning *B* – Boring *EG* – External grinding *IG* – Internal grinding *M* – Milling *DR* – Drilling *RM* – Reaming *HN* – Honing *SF* – Super-finishing	X_1, X_2

3.3.2.2.2 Fuzzy Membership Functions

Typically, a fuzzy set can be written as ordered pairs. For example, the Turning Tolerance set *TT*, shown in Table 3.3, can be written as follows:

$$TT = \{(\mu_{TT}(x_1)/x_1) \mid x_1 \in X_1\}$$

As the Accuracy class X_1 (based on Table 2.3) has a discrete and finite domain, $X_1 = \{1, 2, \ldots, 16\}$, *TT* may be expressed as:

$$TT = {}^{0.33}\!/_{6} + {}^{0.67}\!/_{7} + {}^{1}\!/_{8} + {}^{1}\!/_{9} + {}^{1}\!/_{10} + {}^{0.67}\!/_{11} + {}^{0.33}\!/_{12}$$

where, the expression ${}^{0.33}\!/_{6}$ means that the degree of $x_1 = 6$ belonging to *TT* is *0.33.*

For the tolerance fuzzy sets, as shown in Table 3.3, *{IT} = {TT, BT, EGT, IGT, MT, DRT, RT, HT, SFT},* their membership functions are defined as:

$$IT(x_1) = TT: \quad \mu_{TT}(x_1) = \begin{cases} 0.33 & \text{if } x_1 = 6, 12 \\ 0.67 & \text{if } x_1 = 7, 11 \\ 1 & \text{if } x_1 = 8, 9, 10 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = BT: \quad \mu_{BT}(x_1) = \begin{cases} 0.33 & \text{if } x_1 = 6, 12 \\ 0.67 & \text{if } x_1 = 7, 11 \\ 1 & \text{if } x_1 = 8, 9, 10 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = EGT: \quad \mu_{EGT}(x_1) = \begin{cases} 0.5 & \text{if } x_1 = 5 \\ 1 & \text{if } x_1 = 6, 7 \\ 0.67 & \text{if } x_1 = 8 \\ 0.33 & \text{if } x_1 = 9 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = IGT: \quad \mu_{IGT}(x_1) = \begin{cases} 0.5 & \text{if } x_1 = 5 \\ 1 & \text{if } x_1 = 6, 7 \\ 0.67 & \text{if } x_1 = 8 \\ 0.33 & \text{if } x_1 = 9 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = MT: \quad \mu_{MT}(x_1) = \begin{cases} 0.33 & \text{if } x_1 = 7, 12 \\ 0.67 & \text{If } x_1 = 8, 11 \\ 1 & \text{if } x_1 = 9, 10 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = DRT: \quad \mu_{DRT}(x_1) = \begin{cases} 0.5 & \text{if } x_1=10 \\ 1 & \text{if } x_1=11 \\ 0.67 & \text{if } x_1=12 \\ 0.33 & \text{If } x_1=13 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = RT: \quad \mu_{RT}(x_1) = \begin{cases} 0.33 & \text{if } x_1=5,10 \\ 0.67 & \text{if } x_1=6,9 \\ 1 & \text{if } x_1=7,8 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = HT: \quad \mu_{HT}(x_1) = \begin{cases} 0.5 & \text{if } x_1=4 \\ 0.75 & \text{if } x_1=5 \\ 1 & \text{if } x_1=6,7 \\ 0.5 & \text{if } x_1=8 \\ 0 & \text{otherwise} \end{cases}$$

$$IT(x_1) = SFT: \quad \mu_{SFT}(x_1) = \begin{cases} 0.2 & \text{if } x_1=1 \\ 0.4 & \text{if } x_1=2 \\ 0.6 & \text{if } x_1=3 \\ 0.8 & \text{if } x_1=4 \\ 1 & \text{if } x_1=5,6 \\ 0.67 & \text{if } x_1=7 \\ 0.33 & \text{if } x_1=8 \\ 0 & \text{otherwise} \end{cases}$$

For the surface finish sets: *{IS}={TS, BS, EGS, IGS, MS, DRS, RS, HS, SFS}*, their membership functions are defined as:

$$IS(x_2) = TS: \qquad \mu_{TS}(x_2) = \begin{cases} 0.5 & \text{if } x_2=4,7 \\ 1 & \text{if } x_2=5,6 \\ 0 & \text{otherwise} \end{cases}$$

$$IS(x_2) = BS: \qquad \mu_{BS}(x_2) = \begin{cases} 0.5 & \text{if } x_2=4,7 \\ 1 & \text{if } x_2=5,6 \\ 0 & \text{otherwise} \end{cases}$$

$$IS(x_2) = EGS: \qquad \mu_{EGS}(x_2) = \begin{cases} 0.33 & \text{if } x_2=6,10 \\ 0.67 & \text{if } x_2=7,9 \\ 1 & \text{if } x_2=8 \\ 0 & \text{Otherwise} \end{cases}$$

$$IS(x_2) = IGS: \quad \mu_{IGS}(x_2) = \begin{cases} 0.33 & \text{if } x_2=6,10 \\ 0.67 & \text{if } x_2=7,9 \\ 1 & \text{if } x_2=8 \\ 0 & \text{otherwise} \end{cases}$$

$$IS(x_2) = MS: \quad \mu_{MS}(x_2) = \begin{cases} 0.33 & \text{if } x_2=3,8 \\ 0.67 & \text{if } x_2=4,7 \\ 1 & \text{if } x_2=5,6 \\ 0 & \text{otherwise} \end{cases}$$

$$IS(x_2) = DRS: \quad \mu_{DRS}(x_2) = \begin{cases} 0.5 & \text{if } x_2=4,7 \\ 1 & \text{if } x_2=5,6 \\ 0 & \text{otherwise} \end{cases}$$

$$IS(x_2) = RS: \quad \mu_{RS}(x_2) = \begin{cases} 0.5 & \text{if } x_2=6 \\ 1 & \text{if } x_2=7,8 \\ 0.67 & \text{if } x_2=9 \\ 0.33 & \text{if } x_2=10 \\ 0 & \text{otherwise} \end{cases}$$

$$IS(x_2) = HS: \quad \mu_{HS}(x_2) = \begin{cases} 0.33 & \text{if } x_2=8 \\ 0.67 & \text{if } x_2=9 \\ 1 & \text{if } x_2=10,11 \\ 0.5 & \text{if } x_2=12 \\ 0 & \text{otherwise} \end{cases}$$

$$IS(x_2) = SFS: \quad \mu_{SFS}(x_2) = \begin{cases} 0.5 & \text{if } x_2=9 \\ 1 & \text{if } x_2=10,11 \\ 0.67 & \text{if } x_2=12 \\ 0.33 & \text{if } x_2=13 \\ 0 & \text{otherwise} \end{cases}$$

3.3.2.2.3 Fuzzy Operators

The operation decision depends on the union of tolerance sets and surface finish sets. The output fuzzy set, {OP}, is defined on fuzzy variables X_1 and X_2. According to fuzzy operators (Pedrycy and Gomide, 1998), one can write

$$\{IT\} = \{TT \cup BT \cup EGT \cup IGT \cup MT \cup DRT \cup RT \cup HT \cup SFT\}$$
$$\{IS\} = \{TS \cup BS \cup EGS \cup IGS \cup MS \cup DRS \cup RS \cup HS \cup SFS\}$$

The corresponding membership functions are

$\mu_{IT}(x_1) = max\ [\mu_{TT}(x_1),\ \mu_{BT}(x_1),\ \mu_{EGT}(x_1),\ \mu_{IGT}(x_1),\ \mu_{MT}(x_1),\ \mu_{DRT}(x_1),\ \mu_{RT}(x_1),\ \mu_{HT}(x_1),\ \mu_{SFT}(x_1)]$ $\mu_{IS}(x_2) = max\ [\mu_{TS}(x_2),\ \mu_{BS}(x_2),\ \mu_{EGS}(x_2),\ \mu_{IGS}(x_2),\ \mu_{MS}(x_2),\ \mu_{DRS}(x_2),\ \mu_{RS}(x_2),\ \mu_{HS}(x_2),\ \mu_{SFS}(x_2)]$

Fuzzy operation rules, aggregation and defuzzification are only applied to specific cases. The details about these steps are discussed in the following sections.

3.3.3 Machining Features and their Operations

According to manufacturing practice, a certain machining feature requires its respective operations. It can be found in various manufacturing engineers' handbooks and machinist handbooks (Society of Manufacturing Engineers, 1976). Information about machining features and their feasible operations and machines is built into the system. Abbreviations of operations are defined in Table 3.4 and 15 common features accommodated by the system, listed in Section 3.2.3.1, and their respective operations are summarized in Table 3.5.

Table 3.4. Explanation of Operation Notations

Abbr.	Explanation	Abbr.	Explanation
T	– Turning	RIG	– Rough internal grinding
RT	– Rough turning	FIG	– Finish internal grinding
FT	– Finish turning	HN	– Honing
EG	– Cylindrical grinding	ML	– Milling
REG	– Rough cylindrical grinding	RM	– Rough milling
FEG	– Finish cylindrical grinding	FM	– Finish milling
SF	– Super finishing	TP	– Tapping
B	– Boring	ETT	External thread turning
RB	– Rough boring	ITT	Internal thread turning
SFB	– Semi-finish boring	EGV	– External grooving
FB	– Finish boring	IGV	– Internal grooving
DR	– Drilling	SU	– Surfacing
RDR	– Rough drilling	RSU	– Rough Surfacing
RM	– Reaming	FSU	– Finish surfacing
RRM	– Rough reaming	CDR	– Center hole drilling
FRM	– Finish reaming	CNT	– Counter boring
IG	– Internal grinding	CHA	– Chamfering

Table 3.5. Summary of Machining Features and their Operations

No.	Feature		Feasible Operations	Required Machines
1	External cylinder		Turning, or Turning and Cylindrical grinding, or Turning, Cylindrical grinding and Surface finishing	CNC Turning Center, External Grinder, Surface Finishing Machine
2	External tapered feature		Turning, or Turning and Cylindrical grinding	CNC Turning Center, External Grinder
3	External thread		External thread turning	CNC Turning Center
4	External plane perpendicular to axis		Surfacing	CNC Turning Center
5	External plane parallel to axis		Milling	Vertical Milling Machine, Machine Center
6	External slot		Milling	Milling Machine, Machine Center
7	External groove		Grooving	CNC Turning Center
8	Internal cylinder	Hole diameter $d \le 18$	Drilling, or Drilling and Reaming	CNC Machine Center
		Hole diameter $18 < d \le 50$	Drilling and Boring, or Drilling, Boring and Reaming, or Drilling, Boring and Honing	CNC Turning Center, Honing Machine
		Hole diameter $d > 50$ and $L_{max}/D_{max} > 0.5$	Drilling and Boring, or Drilling, Boring and Honing	CNC Turning Center, Honing Machine
		Hole dia. $d > 50$ and $L_{max}/D_{max} \le 0.5$	Drilling and Boring, Drilling, Boring and Internal grinding	CNC Turning Center, Internal Grinder
9	Internal tapered feature		Boring, or Boring and Internal grinding	CNC Turning Center, Internal Grinder
10	Chamfer		Chamfering	CNC Turning Center
11	Internal thread screw		Internal thread turning	CNC Turning Center
12	Internal groove		Internal grooving	CNC Turning Center
13	Center hole		Center hole drilling	Center Hole Machine
14	Auxiliary holes	Screw thread holes	Drilling and Tapping	Drilling Machine
		Holes without steps	Drilling	Drilling Machine
		Steps	Counter sinking	Drilling Machine
15	Counter		Counter boring	CNC Turning Center

3.3.4 Fuzzy Operation Selection for Individual Features

In this subsection, detailed procedures to develop fuzzy sets and their membership functions for a specific feature, external cylinder, are discussed.

For forming an external cylinder feature, possible processing methods are turning, turning and cylindrical grinding, or turning, cylindrical grinding and surface finishing. The processing capability of a turning operation shown in Table 2.3 is described as follows: For the turning operation, accuracy classes are from 6 to 16. Of them, 6 to 7 classes are highly accurate (these are less frequent applications); 8 to 10 classes are accurate (average applications); 11 to 12 classes are fairly accurate (less frequent applications); and 13 to 16 classes are rough (seldom applications). By manufacturing knowledge, the membership function value of the Turning Tolerance set corresponding to the accurate class is assumed to be 1, the value corresponding to the rough class is assigned to be 0, and the value corresponding to fairly accurate or highly accurate class is linearly distributed between 0 and 1. Thus, a discrete membership function of the Turning Tolerance set can be built, which has a trapezium shape.

The surface quality classes for the turning operation are from one to eight. Similarly, the membership function value corresponding to smooth quality is assumed to be 1, the value corresponding to rough quality is assigned to be 0, and the value corresponding to fairly or very smooth quality is linearly distributed between 0 and 1.

The fuzzy sets and their membership functions for the external cylinder feature are constructed according to the following procedure:

Feature: **External Cylinder**

Step 1: Fuzzy Sets and Linguistic Variables

Three linguistic variables, *{IT}, {IS} and {OP},* are defined for the external cylinder. For the linguistic variable *{IT},* three fuzzy sets are defined:

TT – Turning tolerance set

EGT – External grinding tolerance set

SFT – Surface finish tolerance set

For the linguistic variable *{IS}*, three fuzzy sets are defined:

TS – Turning surface quality set

EGS – External grinding surface quality set

SFS – Surface quality set by surface finishing operation

For the linguistic variable *{OP}*, three fuzzy sets are defined:

T – turning operation set

EG – external grinding operation set

SF– surface-finishing operation set

Therefore, the inputs are $\{IT\} = \{TT, EGT, SFT\}$ and $\{IS\} = \{TS, EGS, SFS\}$. The output is $\{OP\}= \{T, EG, SF\}$. For fuzzy sets on tolerance, $\{IT\} = \{TT, EGT, SFT\}$, their membership functions can be written as:

$$IT(x_1) = TT: \quad \mu_{TT}(x_1) = \begin{cases} 0.33 & if\ x_1=6,12 \\ 0.67 & if\ x_1=7,11 \\ 1 & if\ x_1=8,9,10 \\ 0 & otherwise \end{cases}$$

$$IT(x_1) = EGT: \quad \mu_{EGT}(x_1) = \begin{cases} 0.5 & if\ x_1=5 \\ 1 & if\ x_1=6,7 \\ 0.67 & if\ x_1=8 \\ 0.33 & if\ x_1=9 \\ 0 & otherwise \end{cases}$$

$$IT(x_1) = SFT: \quad \mu_{SFT}(x_1) = \begin{cases} 0.2 & if\ x_1=1 \\ 0.4 & if\ x_1=2 \\ 0.6 & if\ x_1=3 \\ 0.8 & if\ x_1=4 \\ 1 & if\ x_1=5,6 \\ 0.67 & if\ x_1=7 \\ 0.33 & if\ x_1=8 \\ 0 & otherwise \end{cases}$$

These membership functions are shown graphically in Figure 3.5.

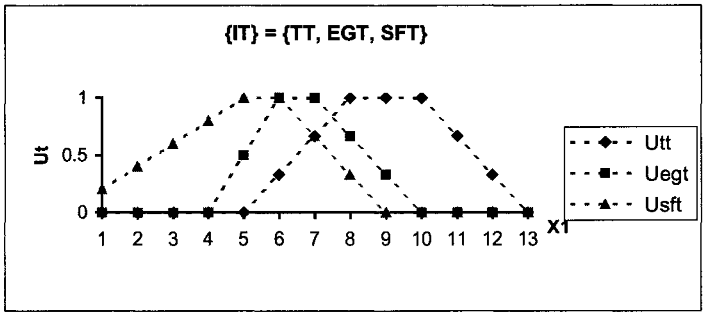


Figure 3.5 Membership Functions for Sets on Tolerance *{IT}*

For fuzzy sets on surface quality, *{S}* = *{TS, EGS, SFS}*, their membership functions are defined as:

$$IS(x_2) = TS: \qquad \mu_{TS}(x_2) = \begin{cases} 0.5 & if\, x_2=4,7 \\ 1 & if\, x_2=5,6 \\ 0 & otherwise \end{cases}$$

$$IS(x_2) = EGS: \qquad \mu_{EGS}(x_2) = \begin{cases} 0.33 & if\, x_2=6,10 \\ 0.67 & if\, x_2=7,9 \\ 1 & if\, x_2=8 \\ 0 & otherwise \end{cases}$$

$$IS(x_2) = SFS: \qquad \mu_{SFS}(x_2) = \begin{cases} 0.5 & if\, x_2=9 \\ 1 & if\, x_2=10,11 \\ 0.67 & if\, x_2=12 \\ 0.33 & if\, x_2=13 \\ 0 & otherwise \end{cases}$$

Figure 3.6 shows these membership functions graphically.

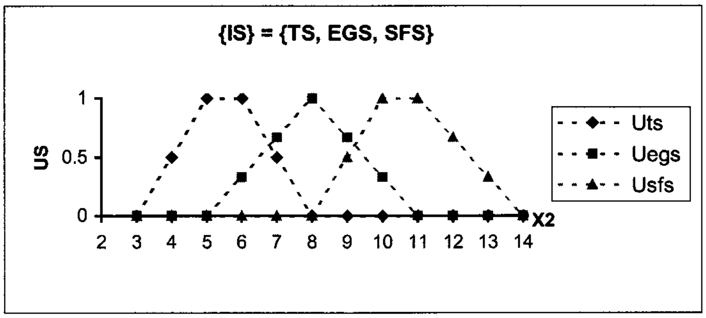


Figure 3.6. Membership Function for Sets on Surface Quality *{IS}*

Step 2: Fuzzy Operations

Based on fuzzy logic, *{IT}* and *{IS}* can be computed as:

$$\{IT\} = \{TT \cup EGT \cup SFT\}$$
$$\{IS\} = \{TS \cup EGS \cup SFS\}$$

That is:

$$\mu_{IT}(x_1) = max\ [\mu_{TT}(x_1), \mu_{EGT}(x_1), \mu_{SFT}(x_1)]$$
$$\mu_{IS}(x_2) = max\ [\mu_{TS}(x_2), \mu_{EGS}(x_2), \mu_{SFS}(x_2)]$$

Step 3: Operation Selection Rules

The operation selection rules are defined as:

R1: *If* ***IT = TT*** *and* ***IS = TS*** *then* ***OP = T***
R2: *If* ***IT = EGT*** *and (****IS = TS*** *or* ***IS = EGS****) then* ***OP = EG***
R3: *If* ***IT = SFT*** *and (****IS = TS*** *or* ***IS = EGS****) then* ***OP = SF***
R4: *If* ***IT = TT*** *and* ***IS = EGS*** *then* ***OP = EG***
R5: *If (****IT = TT*** *or* ***IT = EGT*** *or* ***IT = SFT****) and (****IS = SFS****) then* ***OP = SF***

With fuzzy logic operators **min** for **AND** and **max** for **OR**, the IF_THEN rule can be aggregated into one fuzzy set:

R1: $\mu_1(x_1, x_2) = min\ [\mu_{TT}(x_1), \mu_{TS}(x_2)]$

R2: $\mu_2(x_1, x_2) = min\ \{\mu_{EGT}(x_1), max\ [\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}$

R3: $\mu_3(x_1, x_2) = min\ \{\mu_{SFT}(x_1), max\ [\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}$

R4: $\mu_4(x_1, x_2) = min\ [\mu_{TT}(x_1), \mu_{EGS}(x_2)]$

R5: $\mu_5(x_1, x_2) = min\ \{max[\mu_{TT}(x_1), \mu_{EGT}(x_1), \mu_{SFT}(x_1)], \mu_{SFS}(x_2)\}$

Step 4: Aggregation

Based on fuzzy rules, the membership function of the output can be calculated as follows.

For $\{OP\} = T$, $\mu_T(x_1, x_2) = \mu_1(x_1, x_2) = min\ [\mu_{TT}(x_1), \mu_{TS}(x_2)]$

For $\{OP\} = EG$,

$\mu_{EG}(x_1, x_2) = max\ [\mu_2(x_1, x_2), \mu_4(x_1, x_2)] = max\ \{\ min\ \{\mu_{EGT}(x_1), max\ [\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}, min\ [\mu_{TT}(x_1), \mu_{EGS}(x_2)]\}$

For $\{OP\} = SF$,

$\mu_{SF}(x_1,x_2) = max\ [\mu_3(x_1, x_2), \mu_5(x_1, x_2)] = max\ \{\ min\ \{\mu_{SFT}(x_1), max\ [\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}, min\ \{max[\mu_{TT}(x_1), \mu_{EGT}(x_1), \mu_{SFT}(x_1)], \mu_{SFS}(x_2)\}\}$

Step 5: Defuzzification

Defuyzzification is the mapping of the aggregated output fuzzy set into a single crisp number. There are many methods to do defuzzification (Pedrycz and Gomide ,1998). In this particular application, the Maximum method is used:

$Y' = max\ [\mu_T(x_1, x_2), \mu_{EG}(x_1, x_2), \mu_{SF}(x_1, x_2)]$

In terms of machining principles (shown as Table 2.3), assume that machining operation levels are increased from the lower reachable accuracies towards the higher reachable accuracies. For example, the level of the drilling is lower than the reaming, but the level of the honing is higher than the reaming. The following defuzzification rule is made to lower manufacturing costs: if two or more operation sets have the same maximum membership function value, it is always taken the lower-level operation as the output.

The fuzzy sets and their membership functions for each of 15 individual features are summarized in Table 3.6.

Table 3.6. Summary of Machining Features and their Membership Functions

No.	Feature	Fuzzy Set	Membership Function	Operation Selection Rule	Aggregation	Defuzzification
1	External cylinder	$IT = \{TT, EGT, SFT\}$ $IS = \{TS, EGS, SFS\}$ $OP = \{T, EG, SF\}$	$TT(x_1) = 0.33/6 + 0.67/7 + 1/8 + 1/9 + 1/10 + 0.67/11 + 0.33/12$ $EGT(x_1) = 0.5/5 + 1/6 + 1/7 + 0.67/8 + 0.33/9$ $SFT(x_1) = 0.2/1 + 0.4/2 + 0.6/3 + 0.8/4 + 1/5 + 1/6 + 0.67/7 + 0.33/8$ $TS(x_2) = 0.5/4 + 1/5 + 1/6 + 0.5/7$ $EGS(x_2) = 0.33/6 + 0.67/7 + 1/8 + 0.67/9 + 0.33/10$ $SFS(x_2) = 0.5/9 + 1/10 + 1/11 + 0.67/12 + 0.33/13$	$R1: \mu_1(x_1, x_2) = min[\mu_{TT}(x_1), \mu_{TS}(x_2)]$ $R2: \mu_2(x_1, x_2) = min\{\mu_{EGT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}$ $R3: \mu_3(x_1, x_2) = min\{\mu_{SFT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}$ $R4: \mu_4(x_1, x_2) = min[\mu_{TT}(x_1), \mu_{EGS}(x_2)]$ $R5: \mu_5(x_1, x_2) = min\{max[\mu_{TT}(x_1), \mu_{EGT}(x_1), \mu_{SFT}(x_1)], \mu_{SFS}(x_2)\}$	*For OP=T:* $\mu_T(x_1, x_2) = \mu_1(x_1, x_2) = min[\mu_{TT}(x_1), \mu_{TS}(x_2)]$ Operation: Turning *For OP=EG:* $\mu_{EG}(x_1, x_2) = max[\mu_2(x_1, x_2), \mu_4(x_1, x_2)] = max\{min\{\mu_{EGT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}, min[\mu_{TT}(x_1), \mu_{EGS}(x_2)]\}$ Operation: Turning and Cylindrical grinding *For OP=SF:* $\mu_{SF}(x_1, x_2) = max\{\mu_3(x_1, x_2), \mu_5(x_1, x_2)\} = max\{min\{\mu_{SFT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}, min\{max[\mu_{TT}(x_1), \mu_{EGT}(x_1), \mu_{SFT}(x_1)], \mu_{SFS}(x_2)\}\}$ Operation: Turning, Cylindrical grinding and Surface Finishing	$Y' = max[\mu_T(x_1, x_2), \mu_{EG}(x_1, x_2), \mu_{SF}(x_1, x_2)]$ **
2	External tapered feature	$IT = \{TT, EGT, SFT\}$ $IS = \{TS, EGS, SFS\}$ $OP = \{T, EG, SF\}$	$TT(x_1) = 0.33/6 + 0.67/7 + 1/8 + 1/9 + 1/10 + 0.67/11 + 0.33/12$ $EGT(x_1) = 0.5/5 + 1/6 + 1/7 + 0.67/8 + 0.33/9$ $SFT(x_1) = 0.2/1 + 0.4/2 + 0.6/3 + 0.8/4 + 1/5 + 1/6 + 0.67/7 + 0.33/8$ $TS(x_2) = 0.5/4 + 1/5 + 1/6 + 0.5/7$ $EGS(x_2) = 0.33/6 + 0.67/7 + 1/8 + 0.67/9 + 0.33/10$ $SFS(x_2) = 0.5/9 + 1/10 + 1/11 + 0.67/12 + 0.33/13$	$R1: \mu_1(x_1, x_2) = min[\mu_{TT}(x_1), \mu_{TS}(x_2)]$ $R2: \mu_2(x_1, x_2) = min\{\mu_{EGT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}$ $R3: \mu_3(x_1, x_2) = min\{\mu_{SFT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}$ $R4: \mu_4(x_1, x_2) = min[\mu_{TT}(x_1), \mu_{EGS}(x_2)]$ $R5: \mu_5(x_1, x_2) = min\{max[\mu_{TT}(x_1), \mu_{EGT}(x_1), \mu_{SFT}(x_1)], \mu_{SFS}(x_2)\}$	*For OP=T:* $\mu_T(x_1, x_2) = \mu_1(x_1, x_2) = min[\mu_{TT}(x_1), \mu_{TS}(x_2)]$ Operation: Turning *For OP=EG:* $\mu_{EG}(x_1, x_2) = max[\mu_2(x_1, x_2), \mu_4(x_1, x_2)] = max\{min\{\mu_{EGT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}, max[\mu_{TT}(x_1), \mu_{EGS}(x_2)]\}$ Operation: Turning and Cylindrical grinding *For OP=SF:* $\mu_{SF}(x_1, x_2) = max\{\mu_3(x_1, x_2), \mu_5(x_1, x_2)\} = max\{min\{\mu_{SFT}(x_1), max[\mu_{TS}(x_2), \mu_{EGS}(x_2)]\}, min\{max[\mu_{TT}(x_1),$	$Y' = max[\mu_T(x_1, x_2), \mu_{EG}(x_1, x_2), \mu_{SF}(x_1, x_2)]$ **

						$\mu_{EGT}(x_1)$, $\mu_{SFT}(x_1)]$, $\mu_{SFS}(x_2)\}\}$ Operation: Turning, Cylindrical grinding and Surface Finishing	
3	External thread*						
4	External plane perpendicular to axis*						
5	External plane parallel to axis*						
6	External slot*						
7	External groove*						
8	Internal cylinder	Hole diameter $d \leq 18$	$IT = \{DRT, RT\}$ $IS = \{DRS, RS\}$ $OP = \{DR, RM\}$	$DRT(x_1) = 0.5/10 + 1/11 + 0.67/12 + 0.33/13$ $RT(x_1) = 0.33/5 + 0.67/6 + 1/7 + 1/8 + 0.67/9 + 0.33/10$ $DRS(x_2) = 0.5/4 + 1/5 + 1/6 + 0.5/7$ $RS(x_2) = 0.5/6 + 1/7 + 1/8 + 0.67/9 + 0.33/10$	R1: $\mu_1(x_1, x_2) = min[\mu_{DRT}(x_1), \mu_{DRS}(x_2)]$ R2: $\mu_2(x_1, x_2) = min\{\mu_{RT}(x_1), max[\mu_{DRS}(x_2), \mu_{RS}(x_2)]\}$ R3: $\mu_3(x_1, x_2) = min[\mu_{DRT}(x_1), \mu_{RS}(x_2)]$	*For OP=DR:* $\mu_{DR}(x_1, x_2) = \mu_1(x_1, x_2) = min[\mu_{DRT}(x_1), \mu_{DRS}(x_2)]$ Operation: Drilling *For OP=RM:* $\mu_{RM}(x_1, x_2) = max[\mu_2(x_1, x_2), \mu_3(x_1, x_2)] = max\{min\{\mu_{RT}(x_1), max[\mu_{DRS}(x_2), \mu_{RS}(x_2)]\}, min[\mu_{DRT}(x_1), \mu_{RS}(x_2)]\}$ Operation: Drilling and Reaming	$Y' = max[\mu_{DR}(x_1, x_2), \mu_{RM}(x_1, x_2)]$**

		Hole diameter $18<d\leq50$	$IT = \{BT, RT, HT\}$ $IS = \{BS, RS, HS\}$ $OP = \{B, RM, HN\}$	$BT(x_1)= 0.33/6 + 0.67/7 + 1/8 +1/9 +1/10 +0.67/11 +0.33/12$ $RT(x_1) = 0.33/5 + 0.67/6 +1/7 + 1/8 + 0.67/9 + 0.33/10$ $HT(x_1) = 0.25/1 + 0.25/2 + 0.25/3 + 0.5/4 + 0.75/5 + 1/6 + 1/7 + 0.5/8$ $BS(x_2) = 0.5/4 + 1/5 + 1/6 +0.5/7$ $RS(x_2) = 0.5/6 + 1/7 + 1/8 + 0.67/9 + 0.33/10$ $HS(x_2) = 0.33/8 + 0.67/9 +1/10 + 1/11 + 0.5/12$	$R1: \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ $R2: \mu_2(x_1, x_2) = min\{\mu_{RT}(x_1), max[\mu_{BS}(x_2), \mu_{RS}(x_2)]\}$ $R3: \mu_3(x_1, x_2) = min\{\mu_{HT}(x_1), max[\mu_{BS}(x_2), \mu_{RS}(x_2)]\}$ $R4: \mu_4(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{RS}(x_2)]$ $R5: \mu_5(x_1, x_2) = min\{max[\mu_{BT}(x_1), \mu_{RT}(x_1), \mu_{HT}(x_1)], \mu_{HS}(x_2)\}$	*For OP=B:* $\mu_B(x_1, x_2) = \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ Operation: Drilling and Boring *For OP=RM:* $\mu_{RM}(x_1, x_2) = max[\mu_2(x_1, x_2), \mu_4(x_1, x_2)] = max\{min\{\mu_{RT}(x_1), max[\mu_{BS}(x_2), \mu_{RS}(x_2)]\}, min[\mu_{BT}(x_1), \mu_{RS}(x_2)]\}$ Operation: Drilling, Boring and Reaming *For OP=HN:* $\mu_{HN}(x_1, x_2)=max\{\mu_3(x_1, x_2), \mu_5(x_1, x_2)\} = max\{min\{\mu_{HT}(x_1), max[\mu_{BS}(x_2), \mu_{RS}(x_2)]\}, min\{max[\mu_{BT}(x_1), \mu_{RT}(x_1), \mu_{HT}(x_1)], \mu_{HS}(x_2)\}\}$ Operation: Drilling, Boring and Honing	$Y' = max[\mu_B(x_1, x_2), \mu_{RM}(x_1, x_2), \mu_{HN}(x_1, x_2)]$ **
		Hole diameter $d>50$ and $L_{max}/D_{max} > 0.5$	$IT = \{BT, HT\}$ $IS = \{BS, HS\}$ $OP = \{B, HN\}$	$BT(x_1)= 0.33/6 + 0.67/7 + 1/8 +1/9 +1/10 +0.67/11 +0.33/12$ $HT(x_1) = 0.25/1 + 0.25/2 + 0.25/3 + 0.5/4 + 0.75/5 + 1/6 + 1/7 + 0.5/8$ $BS(x_2) = 0.5/4 + 1/5 + 1/6 +0.5/7$ $HS(x_2) = 0.33/8 + 0.67/9 +1/10 + 1/11 + 0.5/12$	$R1: \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ $R2: \mu_2(x_1, x_2) = min\{\mu_{HT}(x_1), max[\mu_{BS}(x_2), \mu_{HS}(x_2)]\}$ $R3: \mu_3(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{HS}(x_2)]$	*For OP=B:* $\mu_B(x_1, x_2) = \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ Operation: Drilling and Boring *For OP=HN:* $\mu_{HN}(x_1, x_2) = max[\mu_2(x_1, x_2), \mu_3(x_1, x_2)] = max\{min\{\mu_{HT}(x_1), max[\mu_{BS}(x_2), \mu_{HS}(x_2)]\}, min[\mu_{BT}(x_1), \mu_{HS}(x_2)]\}$ Operation: Drilling, Boring and Honing	$Y' = max[\mu_B(x_1, x_2), \mu_{HN}(x_1, x_2)]$ **

		Hole diamer $d>50$ and $L_{max}/D_{max} \leq 0.5$	$IT = \{BT, IGT\}$ $IS = \{BS, IGS\}$ $OP = \{B, IG\}$	$BT(x_1) = 0.33/6 + 0.67/7 + 1/8 + 1/9 + 1/10 + 0.67/11 + 0.33/12$ $IGT(x_1) = 0.5/5 + 1/6 + 1/7 + 0.67/8 + 0.33/9$ $BS(x_2) = 0.5/4 + 1/5 + 1/6 + 0.5/7$ $IGS(x_2) = 0.33/6 + 0.67/7 + 1/8 + 0.67/9 + 0.33/10$	$R1: \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ $R2: \mu_2(x_1, x_2) = min\{\mu_{IGT}(x_1), max[\mu_{BS}(x_2), \mu_{IGS}(x_2)]\}$ $R3: \mu_3(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{IGS}(x_2)]$	*For OP=B:* $\mu_B(x_1, x_2) = \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ Operation: Drilling and Boring *For OP=IG:* $\mu_{IG}(x_1, x_2) = max[\mu_2(x_1, x_2), \mu_3(x_1, x_2)] = max\{min\{\mu_{IGT}(x_1), max[\mu_{BS}(x_2), \mu_{IGS}(x_2)]\}, min[\mu_{BT}(x_1), \mu_{IGS}(x_2)]\}$ Operation: Drilling, Boring and Internal grinding	$Y' = max[\mu_B(x_1, x_2), \mu_{IG}(x_1, x_2)]$ **
9	Internal tapered feature*		$IT = \{BT, IGT\}$ $IS = \{BS, IGS\}$ $OP = \{B, IG\}$	$BT(x_1) = 0.33/6 + 0.67/7 + 1/8 + 1/9 + 1/10 + 0.67/11 + 0.33/12$ $IGT(x_1) = 0.5/5 + 1/6 + 1/7 + 0.67/8 + 0.33/9$ $BS(x_2) = 0.5/4 + 1/5 + 1/6 + 0.5/7$ $IGS(x_2) = 0.33/6 + 0.67/7 + 1/8 + 0.67/9 + 0.33/10$	$R1: \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ $R2: \mu_2(x_1, x_2) = min\{\mu_{IGT}(x_1), max[\mu_{BS}(x_2), \mu_{IGS}(x_2)]\}$ $R3: \mu_3(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{IGS}(x_2)]$	*For OP=B:* $\mu_B(x_1, x_2) = \mu_1(x_1, x_2) = min[\mu_{BT}(x_1), \mu_{BS}(x_2)]$ Operation: Drilling and Boring *For OP=IG:* $\mu_{IG}(x_1, x_2) = max[\mu_2(x_1, x_2), \mu_3(x_1, x_2)] = max\{min\{\mu_{IGT}(x_1), max[\mu_{BS}(x_2), \mu_{IGS}(x_2)]\}, min[\mu_{BT}(x_1), \mu_{IGS}(x_2)]\}$ Operation: Drilling, Boring and Internal grinding	$Y' = max[\mu_B(x_1, x_2), \mu_{IG}(x_1, x_2)]$ **
10	Chamfer*						
11	Internal thread screw*						
12	Internal groove*						
13	Center hole*						
14	Auxiliary holes*						
15	Counter sink*						

* These features have no alternative operations. The fuzzy operation selection approach does not apply to them.

** If two or more operation fuzzy sets have the same membership function value, it is always taken the lower-level operation as the output.

3.3.5 An Example of Operation Generation for an Individual Feature

The example part is shown in Figure 3.1. For the feature F4, its descriptions are given as follows:

Feature Classification: Internal Cylinder (hole)
Dimension: ø20 × 58
Size tolerance grade: H7
Surface finish value: R_a = 1.6 μm (equivalent to surface quality class: 7)

The pre-defined fuzzy sets for the Internal Cylinder, shown in Table 3.7, are given as follows:

Inputs: $IT = \{BT, RT, HT\}$
$IS = \{BS, RS, HS\}$
Output: $OP = \{B, RM, HN\}$

Their membership functions are defined as follows:

$BT(x_1) = 0.33/6 + 0.67/7 + 1/8 + 1/9 + 1/10 + 0.67/11 + 0.33/12$

$RT(x_1) = 0.33/5 + 0.67/6 + 1/7 + 1/8 + 0.67/9 + 0.33/10$

$HT(x_1) = 0.25/1 + 0.25/2 + 0.25/3 + 0.5/4 + 0.75/5 + 1/6 + 1/7 + 0.5/8$

$BS(x_2) = 0.5/4 + 1/5 + 1/6 + 0.5/7$

$RS(x_2) = 0.5/6 + 1/7 + 1/8 + 0.67/9 + 0.33/10$

$HS(x_2) = 0.33/8 + 0.67/9 + 1/10 + 1/11 + 0.5/12$

Membership function values and aggregation are calculated as:

$\mu_{BT}(7) = 0.67;\ \mu_{RT}(7) = 1;\ \mu_{HT}(7) = 1;$
$\mu_{BS}(7) = 0.5;\ \mu_{RS}(7) = 1;\ \mu_{HS}(7) = 0;$

For OP=B:
$\mu_B = \mu_1 = \min\ [\mu_{BT}(7), \mu_{BS}(7)] = \max\ [0.67, 0.5] = 0.5$

For OP=RM:
$\mu_{RM} = \max\ \{\mu_2, \mu_4\} = \max\{\min\{\mu_{RT}(7), \max[\mu_{BS}(7), \mu_{RS}(7)]\}, \min[\mu_{BT}(7), \mu_{RS}(7)]\}$
$= \max\ \{\min[1, \max\ (0.5, 1)], \min\ (0.67, 1)\} = 1$

For OP=HN:

$\mu_{HN} = max(\mu_3, \mu_5)$

$= max\{ min\{\mu_{HT}(7), max[\mu_{BS}(7), \mu_{RS}(7)]\}, min\{max[\mu_{BT}(7),\ \mu_{RT}(7),\ \mu_{HT}(7)],\ \mu_{HS}(7)\}\}$

$= max\{ min[1,\ max\ (0.5,\ 1)],\ min[max\ (0.67,\ 1,\ 1),\ 0]\} = 1$

Based on the defuzzification rule in Table 3.6, one can calculate:

$Y' = max(\mu_{DR}, \mu_{RM}, \mu_{HN}) = 1$, *which is implies OP = RM.*

The crisp output of the operations for the feature F4 is Drilling, Boring and Reaming.

Machining operations for producing the example part, as shown in Figure 3.1, are presented in Table 3.7, which are generated by the IPPS_R system.

Table 3.7. Operations for the Flange

No.	Operation	Machine	Feature ID	Tool approach	Operation explanation
1	1DR - 4	Drilling machine	1	2	Drilling 4 holes (F1) to Ø7
2	2RSU	CNC Turning Center	2	1	Rough surfacing Ø80 (F2)
3	2FSU	CNC Turning Center	2	1	Finish surfacing Ø80 (F2)
4	3SU - 4	Drilling machine	3	2	Surfacing 4 steps Ø15 (F3)
5	4DR	CNC Turning Center	4	3	Drill hole (F4)
6	4B	CNC Turning Center	4	3	Boring F4.
7	4RM	CNC Turning Center	4	3	Reaming F4 to Ø20H7
8	5CHA	CNC Turning Center	5	1	Chamfering F5

3.4 Generation of Preliminary Process Plan

3.4.1 Introduction

This stage re-sequences the operations producing a part and generates a preliminary process plan that satisfies the geometric and technical constraints. The feature relationship matrix reflects these constraints. A preliminary operation sequence is constructed through ranking the machining features and arranging operations by means of their ranks. Such an operation sequence is feasible to form a part.

3.4.2 Ranking the Machining Features

By using the feature relationship matrix, the order of forming features can be determined. The following approach is developed for ordering machining features.

Let I be the set of features to be machined. Clearly, initially $I = \{1, 2, \dots, N_m\}$. Define

$$R_i = \sum_{j=1}^{n} RS_{ij} .$$

Where,

$0 \le R_i \le N_m -1$, since the maximum number of precedent features for a feature is $N_m -1$.

Let $\overline{I}$ be the set of ordered features where the features are ordered from the earliest to be formed to the latest to be processed. Initially, $\overline{I} = \phi$. $\overline{I}$ can be constructed as follows.

For $k = 0$

find all $i \in I_0$ such that

$R_i = k = 0$

Let I_0 contains all i satisfying $R_i = 0$. All features in I_0 can be processed in any order.

Put all $i \in I_0$ in $\overline{I}$ and delete all $i \in I_0$ from I.

For $k = 1$ to $N_m -1$

find all $i \in I$ such that

$R_i = k$

Let I_k contains all i satisfying $R_i = k$

While $I_k \neq \phi$, do

for each $i \in I_k$

find $j_1, j_2, \dots, j_k$ such that $RS_{i,j1} = 1$, $RS_{i,j2} = 1, \dots, RS_{i,jk} = 1$

if $j_1 \in \bar{I}$, $j_2 \in \bar{I}$, ...,and $j_k \in \bar{I}$, put i in $\bar{I}$, delete i from I, and delete i from I_k

If $I \neq \phi$, *continue.*

An example is used to illustrate the procedure. Consider the feature relationship matrix shown in Table 3.8 (Halevi and Weill, 1995).

Table 3.8. Feature Relationship Matrix

	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	0	1	0	0	0	1	0
F2	0	0	0	0	0	1	0	0
F3	0	1	0	0	0	0	0	0
F4	1	0	1	0	0	0	0	0
F5	0	0	0	0	0	0	0	0
F6	0	0	0	0	1	0	0	0
F7	0	0	0	0	0	1	0	1
F8	0	1	0	0	0	1	0	0

The problem can be solved as follows:

Iteration 0: Sum rows of the matrix:

i\j	1	2	3	4	5	6	7	8	R_i
1	0	0	1	0	0	0	1	0	**2**
2	0	0	0	0	0	1	0	0	**1**
3	0	1	0	0	0	0	0	0	**1**
4	1	0	1	0	0	0	0	0	**2**
5	0	0	0	0	0	0	0	0	**0**
6	0	0	0	0	1	0	0	0	**1**
7	0	0	0	0	0	1	0	1	**2**
8	0	1	0	0	0	1	0	0	**2**

Iteration 1:

for $k = 0$, find all $i \in I_0 = \{1, 2, 3, 4, 5, 6, 7, 8\}$, such that $R_i = 0$

$R_5 = 0$, put $i = 5$ in $\bar{I}$. Therefore,

$\bar{I} = \{5\}$ and $I = \{1, 2, 3, 4, 6, 7, 8\}$

Iteration 2:

for $k = 1$, find all $i \in I$ such that $R_i = 1$

$I_1 = \{2,3,6\}$

$i = 2$: $RS_{26} = 1$ and $j_1 = 6 \notin \bar{I}$

$i = 3$: $RS_{32} = 1$ and $j_1 = 2 \notin \bar{I}$

$i = 6$: $RS_{65} = 1$ and $j_1 = 5 \in \bar{I}$

put $i = 6$ in $\bar{I}$, delete $i = 6$ from I, and delete $i = 6$ from I_1

$\bar{I} = \{5, 6\}$ and $I = \{1, 2, 3, 4, 7, 8\}$

$I_1 = \{2,3\}$

$i = 2$: $RS_{26} = 1$ and $j_1 = 6 \in \bar{I}$

$i = 3$: $RS_{32} = 1$ and $j_1 = 2 \notin \bar{I}$

put $i = 2$ in $\bar{I}$, delete $i = 2$ from I, and delete $i = 2$ from I_1

$\bar{I} = \{5, 6, 2\}$ and $I = \{1, 3, 4, 7, 8\}$

$I_1 = \{3\}$

$i = 3$: $RS_{32} = 1$ and $j_1 = 2 \in \bar{I}$

put $i = 3$ in $\bar{I}$, delete $i = 3$ from I, and delete $i = 3$ from I_1

$\bar{I} = \{5, 6, 2, 3\}$ and $I = \{1, 4, 7, 8\}$

$I_1 = \phi$

for $k = 2$, find all $i \in I$ such that $R_i = 2$

$I_2 = \{1, 4, 7, 8\}$

$i = 1$: $RS_{13} = 1, RS_{17} = 1,\ j_1 = 3 \in \bar{I}$ and $j_2 = 7 \notin \bar{I}$

$i = 4$: $RS_{41} = 1, RS_{43} = 1, j_1 = 1 \notin \bar{I}$ and $j_2 = 3 \in \bar{I}$

$i = 7$: $RS_{76} = 1, RS_{78} = 1,\ j_1 = 6 \in \bar{I}$ and $j_2 = 8 \notin \bar{I}$

$i = 8$: $RS_{82} = 1, RS_{86} = 1,\ j_1 = 2 \in \bar{I}$ and $j_2 = 6 \in \bar{I}$

put $i = 8$ in $\bar{I}$, delete $i = 8$ from I, and delete $i = 8$ from I_2

$\bar{I} = \{5, 6, 2, 3, 8\}$ and $I = \{1, 4, 7\}$

$I_2 = \{1, 4, 7\}$

$i = 1$: $RS_{13} = 1, RS_{17} = 1,\ j_1 = 3 \in \bar{I}$ and $j_2 = 7 \notin \bar{I}$

$i = 4$: $RS_{41} = 1, RS_{43} = 1, j_1 = 1 \notin \bar{I}$ and $j_2 = 3 \in \bar{I}$

$i = 7$: $RS_{76} = 1, RS_{78} = 1,\ j_1 = 6 \in \bar{I}$ and $j_2 = 8 \in \bar{I}$

put $i = 7$ in $\bar{I}$, delete $i = 7$ from I, and delete $i = 7$ from I_2

$\overline{I} = \{5, 6, 2, 3, 8, 7\}$ and $I = \{1, 4\}$

$I_2 = \{1, 4\}$

$i = 1$: $RS_{13} = 1$, $RS_{17} = 1$, $j_1 = 3 \in \overline{I}$ and $j_2 = 7 \in \overline{I}$

$i = 4$: $RS_{41} = 1$, $RS_{43} = 1$, $j_1 = 1 \notin \overline{I}$ and $j_2 = 3 \in \overline{I}$

put $i = 1$ in $\overline{I}$, delete $i = 1$ from I, and delete $i = 1$ from I_2

$\overline{I} = \{5, 6, 2, 3, 8, 7, 1\}$ and $I = \{4\}$

$I_2 = \{4\}$

$i = 4$: $RS_{41} = 1$, $RS_{43} = 1$, $j_1 = 1 \in \overline{I}$ and $j_2 = 3 \in \overline{I}$

put $i = 4$ in $\overline{I}$, delete $i = 4$ from I, and delete $4 = 1$ from I_2

$\overline{I} = \{5, 6, 2, 3, 8, 7, 1, 4\}$ and $I = \phi$

The feature order is 5→6→2→3→8→7→1→4. Using the graphic method, Halevi and Weill (1995) also give the order as 5→6→2→3→8→7→1→4, as shown below.

	F1	F2	F3	F4	F5	F6	F7	F8	1	2	3	4	5	6	7	8
F1	0	0	1	0	0	0	1	0							⊗	
F2	0	0	0	0	0	1	0	0			⊗					
F3	0	1	0	0	0	0	0	0				⊗				
F4	1	0	1	0	0	0	0	0								⊗
F5	0	0	0	0	0	0	0	0	⊗							
F6	0	0	0	0	1	0	0	0		⊗						
F7	0	0	0	0	0	1	0	1						⊗		
F8	0	1	0	0	0	1	0	0					⊗			

3.4.3 Generation of Preliminary Process Plan

A preliminary process plan is determined by sequencing the operations produced in previous stage based on the ordering of the features. Accordingly, operations listed in Table 3.7 are arranged in the following sequence, as shown in Table 3.9.

Table 3.9. The Preliminary Process Plan for the Flange

No.	Operation	Machine	Feature ID	Tool approach	Operation Explanation
1	2RSU	CNC Turning Center	2	1	Rough surfacing Ø80 (F2)
2	2FSU	CNC Turning Center	2	1	Finish surfacing Ø80 (F2)
3	4DR	CNC Turning Center	4	3	Drill hole (F4)
4	4B	CNC Turning Center	4	3	Boring F4.
5	5CHA	CNC Turning Center	5	1	Chamfering F5.
6	4RM	CNC Turning Center	4	3	Reaming F4 to Ø20H7
7	1DR - 4	Drilling machine	1	2	Drilling 4 holes (F1) to Ø7
8	3SU - 4	Drilling machine	3	2	Surfacing 4 steps Ø15 (F3)

3.5 Selection of Setups and Heuristic Search of Operation Sequences

3.5.1 Setup Selection

Setup refers to a unique locating, supporting and clamping configuration (Chang, et al., 1998). That is, a work-piece is held in a fixture with a certain orientation during machining. Due to the positioning and clamping, not all the machining features can be accessed in one setup. Only those with the same cutting direction and being processed on a same machine can be accessed in one setup.

Selection of setups is realized by grouping operations with the same tool approach direction and machine resource. It is presented as follows:

Let $O = \{O_1, O_2, \ldots, O_m\}$ be the sequence of operations to be processed, M_j denote the machine resource for operation O_j, $j = 1, 2, \ldots, m$, and , A_j represent the tool approach direction for operation O_j, $j = 1, 2, \ldots, m$.

Moreover, let $\overline{O} = \{G_1, G_2, \ldots, G_k\}$ be the sequence of groups of operations where each group G_i, $i = 1, 2, \ldots, k$, utilizes the same machine resource and can be accessed from the same direction. The groups of operations G_i, $i = 1, 2, \ldots, k$, can be constructed as follows.

For $j = 1$

  Put O_j in G_1

For $j = 2$ to m

  For each operation $O_j \in O$, find M_j and A_j

  If $M_j = M_{j-1}$ and $A_j = 3$, put O_j in G_i

  If $M_j = M_{j-1}$ and $(A_j = A_{j-1}$ or $A_j = 3$), put O_j in G_i

  Otherwise, put O_j in G_{i+1}

Based on the operation grouping method, the preliminary process plan for the Flange given in Table 3.9 is grouped into the following two setups:

```
Setup 1:
Machine: CNC Turning Center
Tool approach: left
Op1: 2RSU (Rough surfacing the surface F2)
Op2: 2FSU (Finish surfacing the surface F2)
Op3: 4DR (Drill the hole F4)
Op4: 4B (Boring the hole F4)
Op5: 5CHA (Chamfering F5)
Op6: 4RM (Reaming the hole F4 to Ø20H7)
Setup 2:
Machine: Drilling machine
Tool approach: right
Locating Datum: F2
Clamping Datum: B1
Op7:  1DR-4 (Drilling 4 holes F1 to Ø7)
Op8: 3RSU (Surfacing 4 steps F3 to Ø15)
```

3.5.2 Heuristic Search of Operation Sequence

Process planning optimization is a hot topic in current computer-aided process planning research. As discussed in Chapter 2, most research on optimization concentrated on cutting parameters or machine power. The proposed system considers this problem through reducing the number of setups. The breadth-first search technique is applied to find a heuristic solution.

The primary objective of manufacturing is to provide a component or product according to the design with the least production cost and time. However, setup changes involve unclamping and removing the work-piece from one fixture, then locating and clamping it into another fixture. Not only will these changes affect manufacturing quality but impact on productivity and cost.

The setup changes, which mean a work-piece being processed by different reference datum, increase accumulative errors of both dimensions and positions of a work-piece. Furthermore, they lead to the increase of production time, since unclamping, locating and clamping actions require certain operating times. Finally, increasing the number of fixtures also leads to the increase of production cost. Clearly, the number of setups plays a key role in a process plan. It is necessary to reduce the number of setups to increase the accuracy and to reduce production time.

A heuristic search algorithm is developed to search the process plan with the least number of setups. The heuristic search problem can be defined as follows:

Find the process plan with the least number of setups, subject to:

1. *The geometrical constraints as expressed by the feature relationship matrix.*
2. *The machining technical constraints:*
    a. *The machining sequences follow the orders from chip removing processes to abrasion processes.*
    b. *If a hole with a chamfer is processed by more than two operations, then the chamfering operation has to be carried out before the finish operation of the hole. Otherwise, the chamfer is processed after the hole.*

c. *A grove has to be processed after its adjacent features.*

d. *If feature i is the reference datum of feature j, and j has more than one operation, then the rough operation of j has to be processed before i, and the final operation of j has to be processed after i.*

e. *For the external features, the rough operation processing follows the orders from the larger diameter to the smaller one; for the internal features, it follows the ascent diameter orders.*

The breadth-first search technique (Rich and Knight, 1991) is used to search the final process plan with the minimum number of setups. The procedure for the breadth-first search is:

1. Set the preliminary process plan as the initial reference plan, and the number of setups as the current lower bound of setups.
2. Search all possible plans until the final process plan is found.
    1) Apply rules to generate a new process plan.
    2) Group operations and find the number of setups for the new process plan.
    3) If the number of setups for the new process plan is less than the current lower bound, set the new plan as the current reference plan and the number of setups as the current lower bound.
    4) The search stops if the new plan is the same as the previous plan or a fixed number of plans that have the same number of setups appear successively.

Specifically, let the initial process plan as $O = \{O_1, O_2, \ldots, O_u, \ldots, O_n\}$. All new process plans considered can be generated as follows.

For u=2 to n

For j=u-1 to 1

If after the positions of O_j and O_u in the plan are switched, the new plan satisfies the geometric constraints and machining technical constraints, then switch the positions of O_j and O_u in the plan to generate a new process plan as $\overline{O} = \{O_1, O_2, \ldots, O_{j-1}, O_u, O_j, \ldots, O_{n-1}, O_n\}$.

For an example of heuristic search processes, please see Chapter 5.

3.6 System Design

The IPPS_R system is an automated process planning system developed in the Visual C++ environment by utilizing Microsoft Foundation Class (MFC), which is capable of installation and operation on a PC. The system includes three sub-systems:

- User Interface (dialog boxes, property sheets and display sheets)
- Process Generation, and
- Knowledge Base.

The interaction of sub-systems of the IPPS_R system works as follows: the specific inputs of a part are sent to the system through lists of dialog boxes or property sheets in *User Interface*. *Process Generation* sub-system processes data from the inputs, retrieves information from *Knowledge Base*, generates a part code and operations for each feature, builds the feature relationship matrix, ranks features, produces a preliminary process plan, selects setups and optimizes operation sequences. *Knowledge Base* stores rules, algorithms and knowledge for generating a process plan. Intermediate results, final results and notations are displayed in the display sheets of *User Interface*. A schematic diagram of the system is shown in Figure 3.7, and the mechanism of the system is illustrated in Figure 3.8.

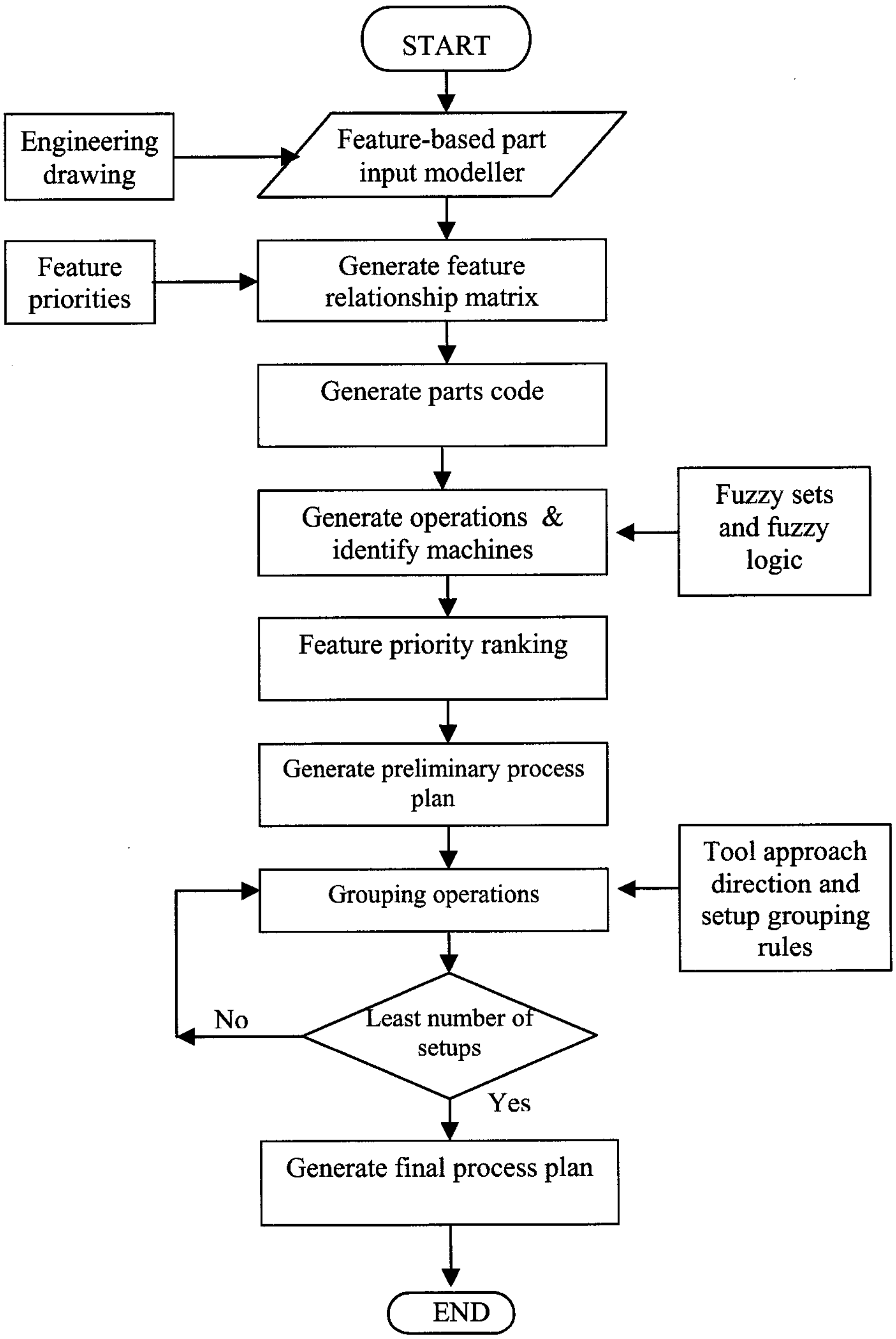


Figure 3.7. Schematic Diagram of the IPPS_R System

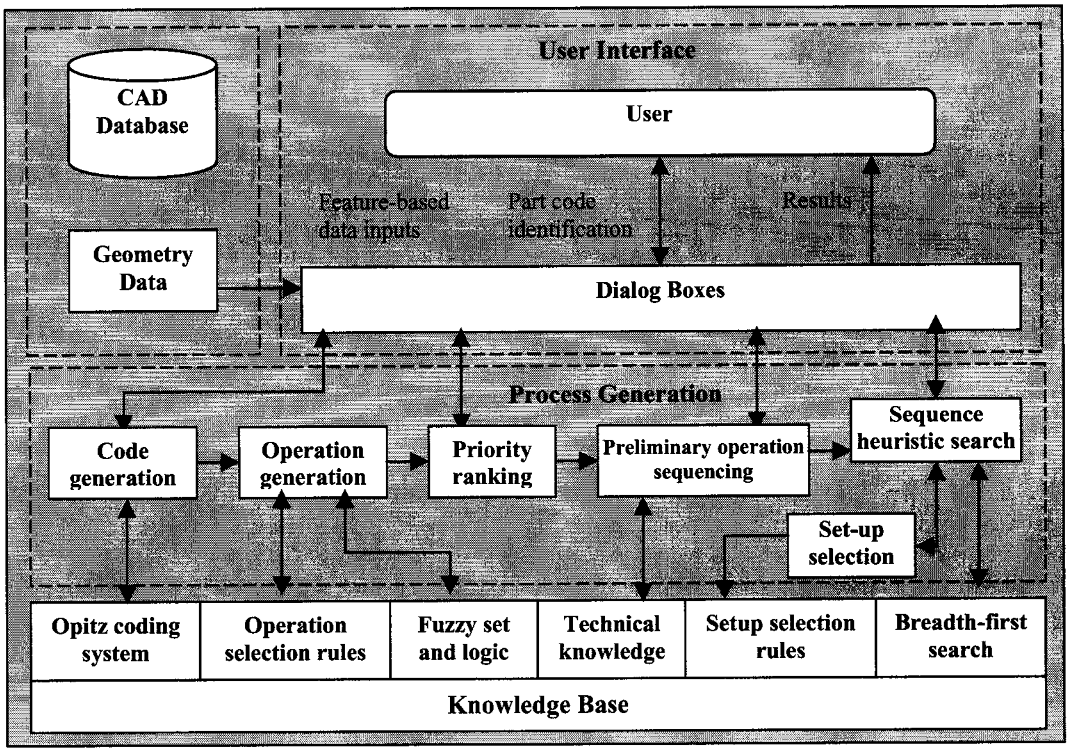


Figure 3.8. Mechanism of the IPPS_R System

3.7 Sub-Systems of the IPPS_R System

3.7.1 User Interface

User Interface sub-system is designed to carry out case-specific data inputs and part code identification and display intermediate and end results, which is composed of a series of dialog boxes. *User Interface* contains three modules:

- The *Case-specific Data Inputs* module.
- The *Part Code Identification* module.
- The *Display* module.

3.7.1.1 Feature-based Data Inputs Module

The *Case-specific Data Inputs* module includes three units:

- *Part Drawing Input,*
- *Maximum Dimension Input, and*
- *Feature Information Input.*

The *Part Drawing Input* unit plays the function of storing and displaying the geometric models of the components to be planned. A manufacturing component can be represented with its geometry model plus its technical specifications. The geometric model is a collection of machining features with shapes, sizes and accuracies. The *Parts Drawing Input* unit provides a tool to display parts' geometry model visually. Although currently the technical data required by the system cannot be produced automatically from the geometric model, the automatic conversion from a geometric model to its data can be incorporated into the system in future research.

The *Maximum Dimension Input* unit allows a user to input overall sizes of the components to be processed. The *Feature Information Input* unit is designed with a series of dialog sheets which allow a user to input geometric and technical data defined in the part representation model. In this unit, machining features of rotational parts are classified into 15 types, each machining feature requiring some specific operations based on its tolerance and surface quality grades. The characteristics of a feature are represented with its type, sizes, tolerances, surface finish, tool approach direction, and its relationships to the other features.

3.7.1.2 Part Code Identification Module

The *Part Code Identification* module is used to identify these characteristics required for building a part code. The module is designed as a series of dialog sheets. The characteristics are determined through user-computer interactions.

3.7.1.3 Display Module

The *Display* module displays the intermediate and final results generated from the *User Interface*, *Process Generation* and *Knowledge Base* sub-systems.

3.7.2 Knowledge Base Sub-System

The Knowledge Base stores necessary rules and knowledge to produce a process plan. It includes:

(1) *The Opitz coding system*: A part classification coding system where a part is represented by a nine decimal digit code. Of them, the first five decimal digits represent the geometric properties of a part and the remaining four decimal digits describe the major dimension, material type, material form, and accuracy.

(2) *Operation selection rules*: The operation selection rules that the system employs, which are based on manufacturing principles.

(3) *Fuzzy sets and fuzzy logic*: Fuzzy logic is a technique for dealing with problems with vague, imprecise and uncertain information. This method mimics the human's approximated reasoning logic to solve uncertain or imprecise problems by applying exact rules. The foundation of fuzzy logic is fuzzy set theory. Contrary to the crisp set, each member of a fuzzy set belongs to it to some degree. By mathematical representation, a fuzzy set is usually expressed as its membership values between the interval of 0 to 1.

(4) *The operation priority knowledge*: The priority knowledge comes from machining knowledge that has been accumulated from manufacturing practices or from experiences. Setup selection rules: rules for grouping operations.

(5) *The breadth-first search technique*: It is one of AI techniques. This method is applied to search a solution in a tree-structured problem. Starting from the first node, new nodes are generated by applying rules. If the new node is the final state, stop

searching iteration. Otherwise, repeat for the next element. If more than one node exists, the search repeats for the next node.

3.7.3 Process Generation Sub-System

The *Process Generation* sub-system includes six modules: (i) part code generation, (ii) operation generation, (iii) feature priority ranking, (iv) preliminary operation sequencing, (v) setup selection, and (vi) sequence heuristic search. The code generation module generates an Opitz code for the part. The operation generation module generates operations and selects machines for each feature, which is based on fuzzy sets and fuzzy logic. The feature priority ranking module ranks feature processing orders according to the feature relationship matrix. The preliminary operation sequencing module produces the preliminary process plan based on geometric constraints of a part. The setup selection module groups operations based on tool access directions and machines. The sequence heuristic search module generates the final process plan that is the result of heuristically searching feasible process plans.

Chapter 4: User Interface for the IPPS_R System

The IPPS_R system, presented in Chapter 3, is an automated machining process planning system for rotational parts. In this chapter, the system implementation and user interface are demonstrated.

4.1 Implementation of the IPPS_R System

The IPPS_R system is implemented in Microsoft Visual C++ 6.0 on a personal computer, using Microsoft Foundation Class (MFC). The implementation process requires creating a user interface which connects the Data Input, Process Generator and Display components. In the Data Input component, a series of dialog boxes and property sheets are designed for a user to input and to identify feature-based part representation models. In the Process Generator component, all functions, such as processing input data, calling functions, carrying out computations and generating process plans, are implemented in Visual C++ 6.0 and are linked to the system through control elements. In the Display component, display sheets and windows are implemented for showing intermediate and final results, which cannot be directly modified by a user.

The system provides a highly intuitive user interface and no special computer software background is required. All functions are activated by control buttons, dialog boxes, or property sheets.

4.2 Main Screen of the IPPS_R System

The main screen of the IPPS_R system is a dialog-based interface that includes three components: Data Input, Process Generator, and Display, as shown in Figure 4.1. The Data Input component links to its sub-dialog boxes or property sheets through its control elements, which allow a user to input and to modify information about a part. The Process Generator component, with six processing modules, carries out designated tasks to generate a process plan. The Display component shows notations and intermediate and final results. The system components and their control elements are listed in Table 4.1.

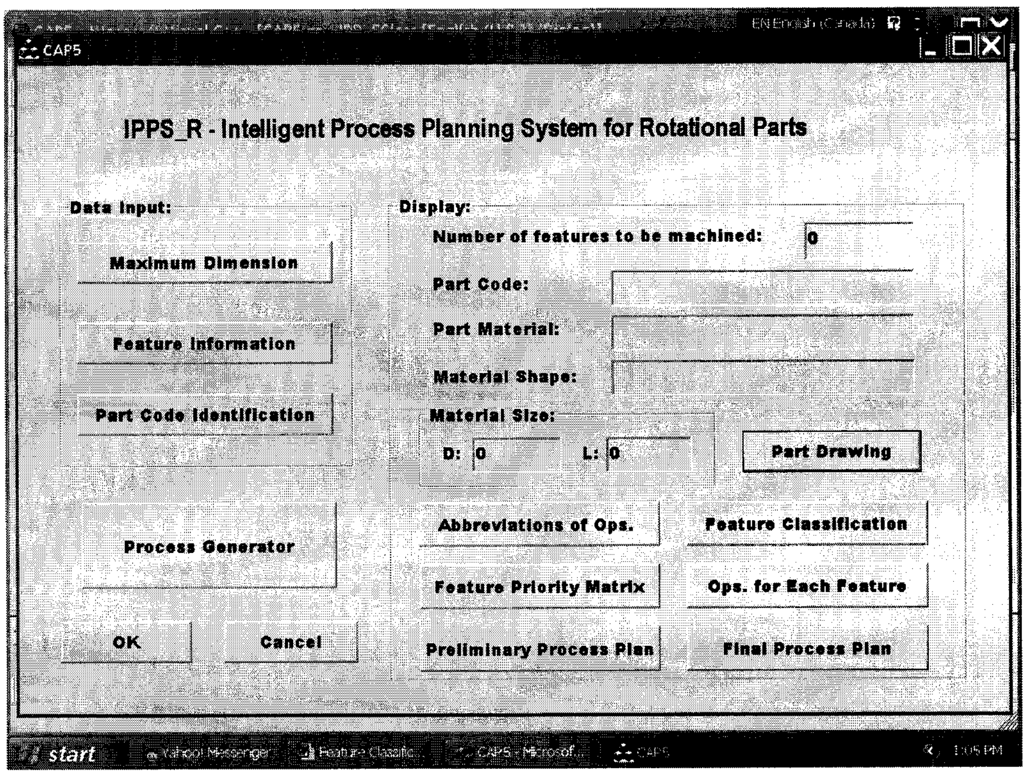


Figure 4.1. Main Screen of the IPPS_R System

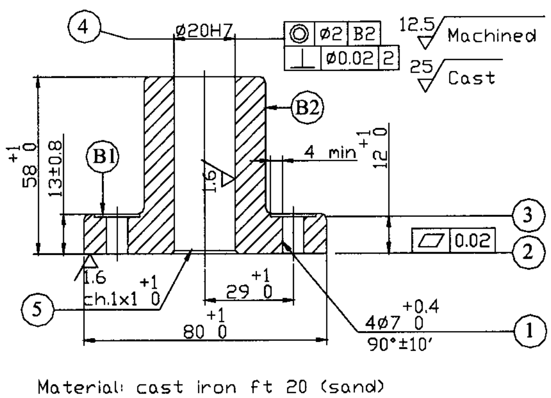
Table 4.1. Functions of System Components and their Control Elements

Component	Control Element	Function
Data Input	**Maximum Dimension**	Call a dialog box to allow a user to input overall dimensions of a part
	Feature Information	Control a series of dialog boxes to allow a user to input detailed information about a part. It includes the total number of features to be machined, and each individual feature's geometric type, dimension, size tolerance, surface finish and tooling approach direction, as well as priorities among features.
	Part Code Identification	Call a property sheet to identify the code for a part, which includes identifying the part's class, geometric shapes, maximum dimensions, accuracies, materials and material shapes.
Process Generator	**Process Generator**	Link to the six processing modules: • Code Generation module: calculate raw material sizes, build the feature priority matrix (feature relationship matrix), and generate the Opitz code of a part. • Operation Generation module: generate operations for each feature of a part and select machines. • Feature Priority Ranking module: rank the processing priorities of features • Preliminary Operation Sequencing module: produce a preliminary process plan for the part. • Setup Selection module: group operations and select setup plans by means of tool approach direction and machine. • Sequence heuristic search module: optimize operation sequences by minimizing the total number of setups and select a final process plan.
Display	**Number of features to be machined**	Display the total number of the features of a part to be machined, which is inputted by a user
	Part Code	Display the Opitz code of a part generated by the system
	Part Material	Display the material name of a part
	Material Shape	Display the material shape and form of a part
	Material Size	Display the material sizes of a part
	Part Drawing	Display the drawing of a part to be processed, which can be pre-stored by a user
	Abbreviations of Operations.	Display operation notations adopted by the system
	Feature Classifications	Display 15 types of the features defined by the system
	Feature Priority Matrix	Display the feature relationship matrix built by the system
	Operations for Each Feature	Display the operations of a part generated by the system
	Preliminary Process Plan	Display the preliminary process plan generated by the system
	Final Process Plan	Display the final process plan of a part which is optimized by the system

4.3 Interface Screens of the IPPS_R System

In this section, user interface screens of the IPPS_R system are introduced through an application of the system to an example part, a Flange, as shown in Figure 4.2.

Sample Component: Flange



Source: Halevi and Weill (1995), Principles of Process Planning: A Logical Approach, pp.16-19, Chapman & Hall, London, U.K.

Figure 4.2. A Sample Part: Flange

4.3.1 Part Description Form

A part description form for the Flange is shown in Table 4.2, which is inputted by a user manually.

Table 4.2. Part Description Form for the Flange

Feature ID	Feature description	Length (mm)	Diameter (mm)	Tolerance grade number	Surface finish class	Precedent features	Tool approach
F1	Auxiliary holes	12	$\phi 7 \times 4$	11	4	F4	Right
F2	End face		$\phi 80$	7	7	B1	Left
F3	Auxiliary steps	0.5	$\phi 15 x 4$			F1, F4	Right
F4	Internal hole (through)	58	$\phi 20$	7	7	F2, F5, B2	Both
F5	Chamfer		$\phi 20 x 1 x 1$	11	4	F2	Left

Material: Gray Cast
Material form: Cast
Other surfaces: Ra=12.5μm (machined), Ra=25.4 μm (cast)
Note: For equivalent surface finish classes and tolerance grades to these values, please see Table 2.1 and Table 2.2.

4.3.2 Part Description Data Input

When being run on a PC, the Main Screen (Figure 4.1) of the IPPS_R system is presented. Input functions are carried out by the *Data Input* component. The *Data Input* component is composed of three control buttons: *Maximum Dimension*, *Feature Information* and *Part Code Identification*. The *Maximum Dimension* button activities a dialog box as shown in Figure 4.3, which allows a user to input overall sizes of a part. The *Feature Information* button links a dialog box named *Feature Information*, as given in Figure 4.4, which allows a user to input detailed part descriptions. The *Part Code Identification* button connects to a property sheet –*Part Code Identification* sheet, which allows a user to identify information associated with part code generation.

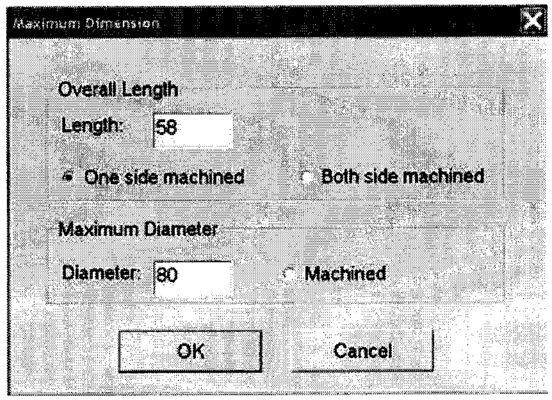


Figure 4.3. Maximum Dimension Screen

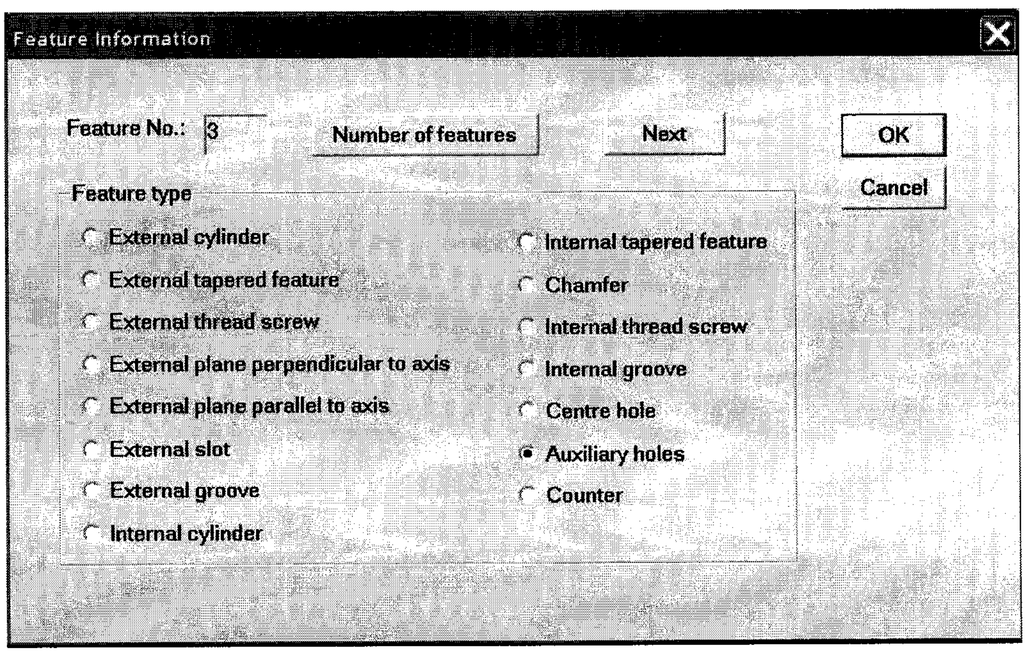


Figure 4.4. Feature Information Screen

On the *Feature Information* dialog box screen, click *Number of Features* button first to input the total number of features to be machined, and then to input the detailed information about a feature. Click a radio button in the *Feature type* group boxes to identify a feature's classification. Subsequently, click *Next* button to call the *Input Feature Details* dialog boxes, as shown in Figure 4.5 and Figure 4.6. A feature's sizes, tolerance grade numbers and surface finish classes (ISO standards), tool approach direction (cutting critical path), and cutting priorities are inputted. The detailed information about other features is similarly gathered.

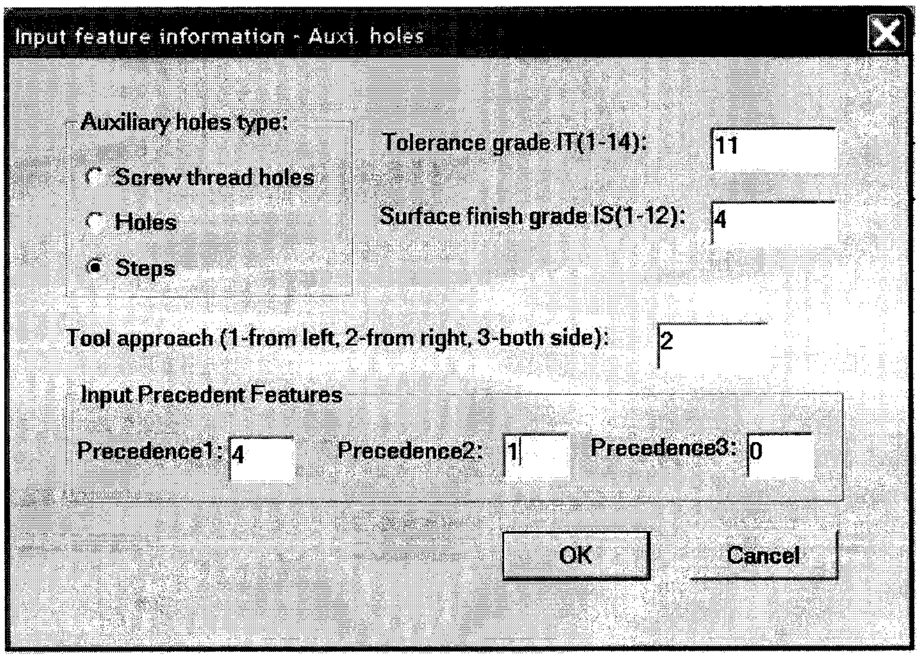


Figure 4.5. Input Feature Information – Auxiliary Holes Screen 1

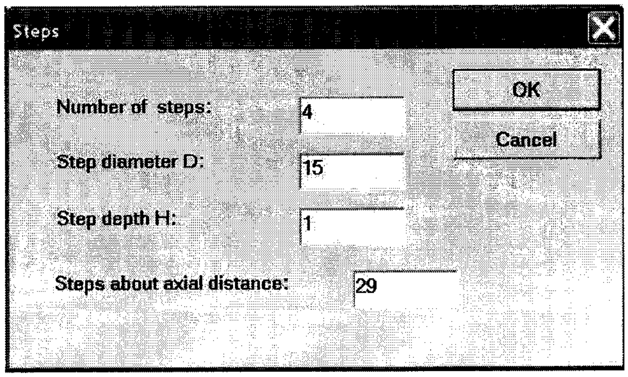


Figure 4.6. Input Feature Information – Auxiliary Holes Screen 2

The next stage is to prepare information for the generation of a part code. The *Part Code Identification* sheet is composed of nine property pages, shown in Figure 4.7 to Figure 4.15. The Opitz code contains 9 decimal digits, and each one represents a type of property for part representation. Correspondingly, each page is designed to identify one respective property.

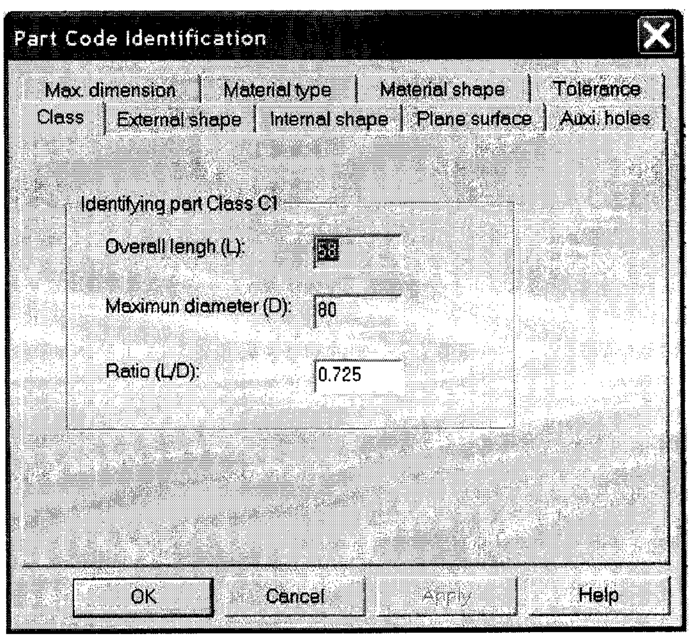


Figure 4.7. Part Code Identification Sheet – Part Class Page

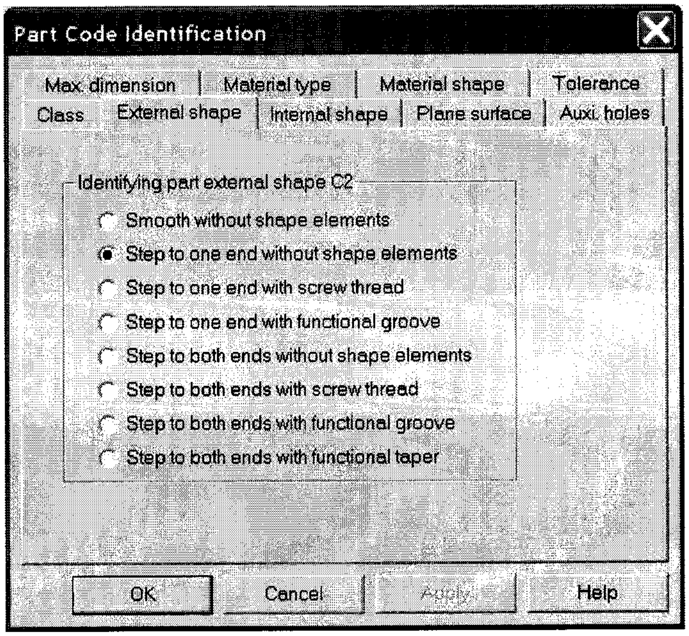


Figure 4.8. Part Code Identification Sheet – External Shape Page

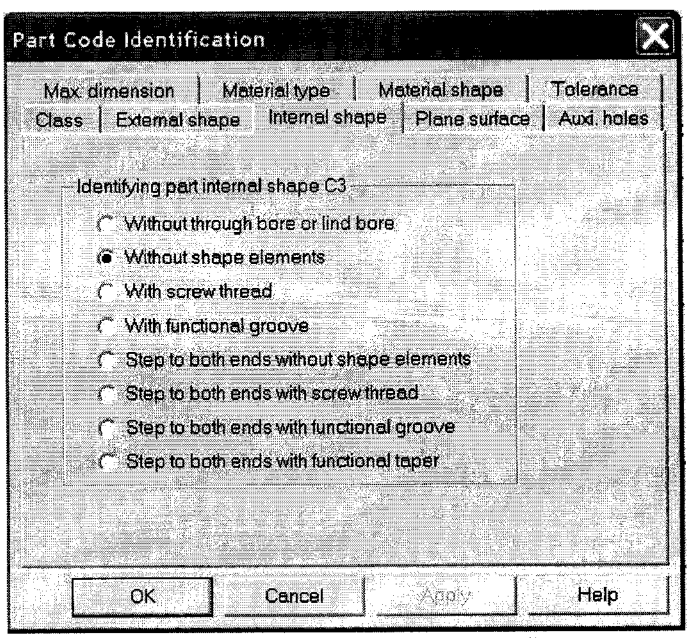


Figure 4.9. Part Code Identification Sheet – Internal Shape Page

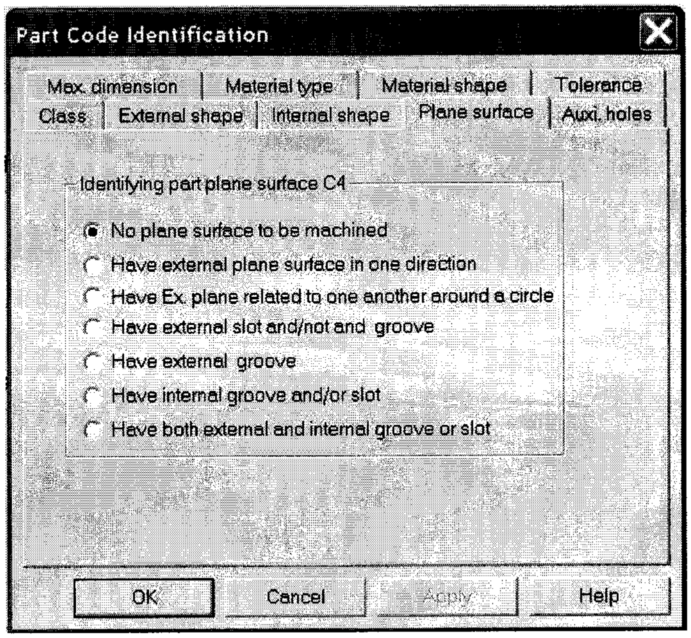


Figure 4.10. Part Code Identification Sheet – Plane Surface Page

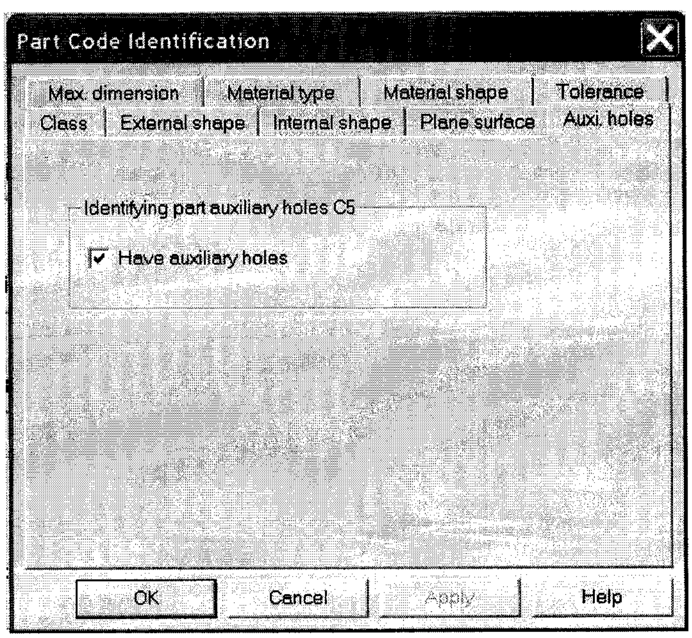


Figure 4.11. Part Code Identification Sheet – Auxiliary Hole Page

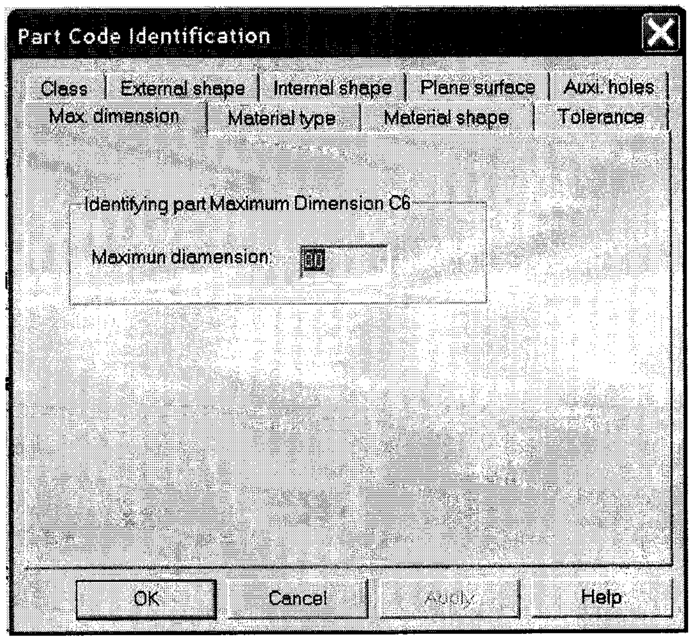


Figure 4.12. Part Code Identification Sheet – Maximum Dimension Page

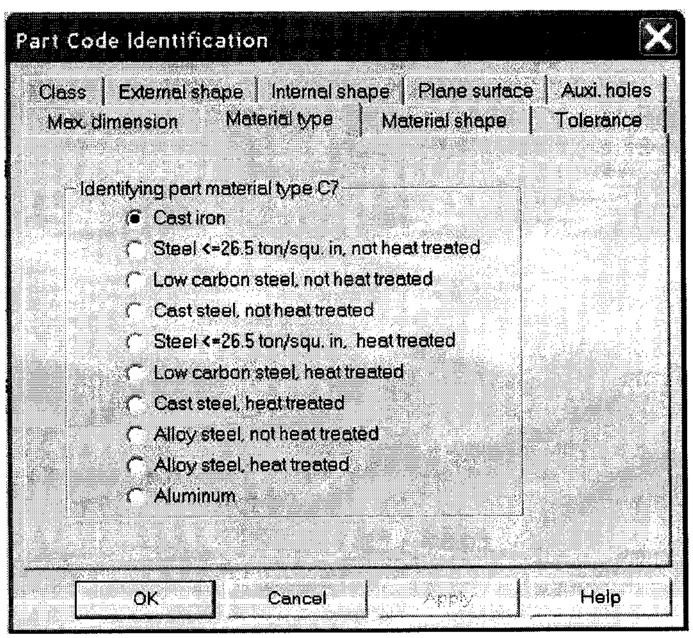


Figure 4.13. Part Code Identification Sheet – Material Type Page

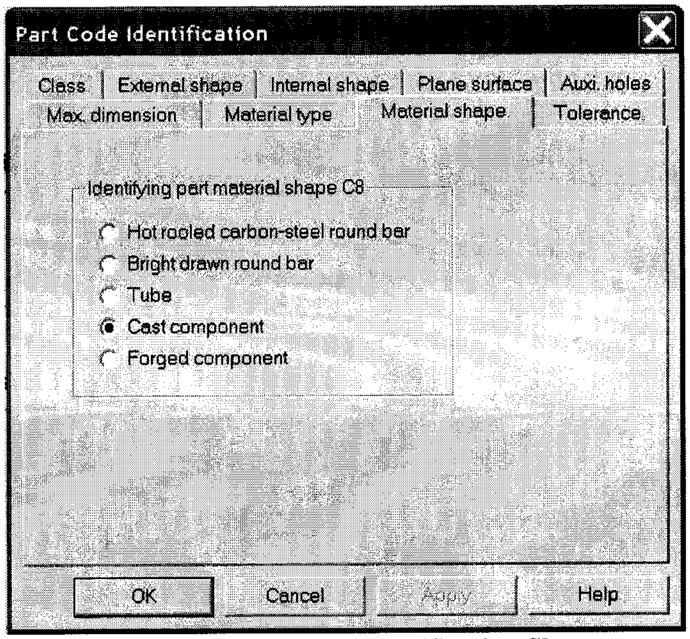


Figure 4.14. Part Code Identification Sheet - Material Shape Page

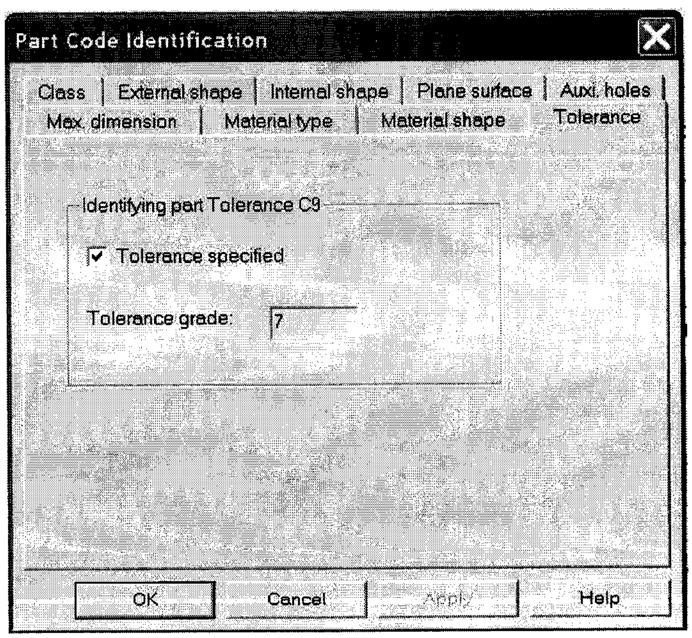


Figure 4.15. Part Code Identification Sheet - Tolerance Page

4.3.3 Processing and Display

After all information for the part representation is collected, click the *Process Generator* button and all the processing modules are activated. As soon as the "Processing Successful" message appears, the results of process planning can be found in the *Display* component. The *Display* component includes text boxes and control buttons linked to relevant display sheets, which cannot be modified by a user. These text boxes and display sheets, shown in Figure 4.16 to Figure 4.23, exhibit notations and intermediate and final results for the process planning.

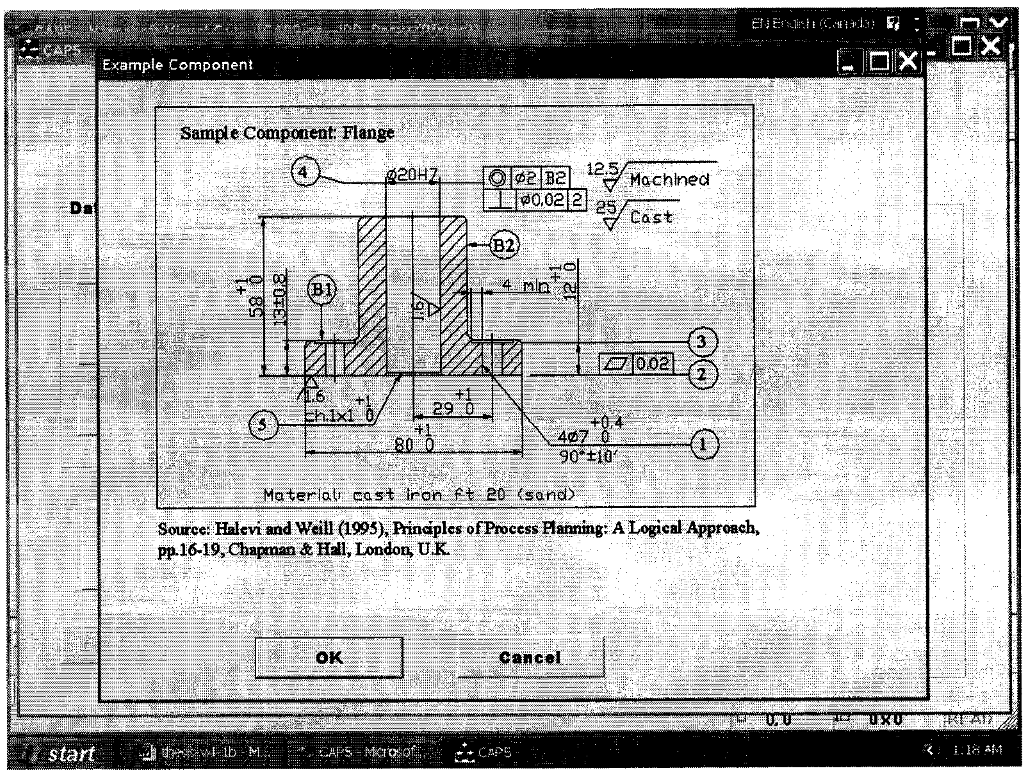


Figure 4.16. Drawing Display Sheet

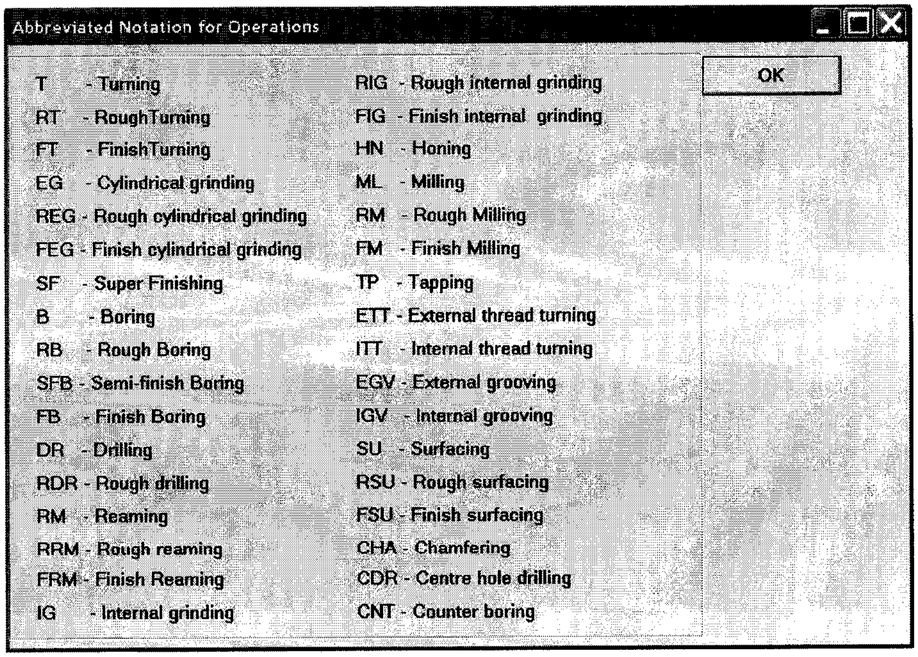


Figure 4.17. Notation Display Sheet

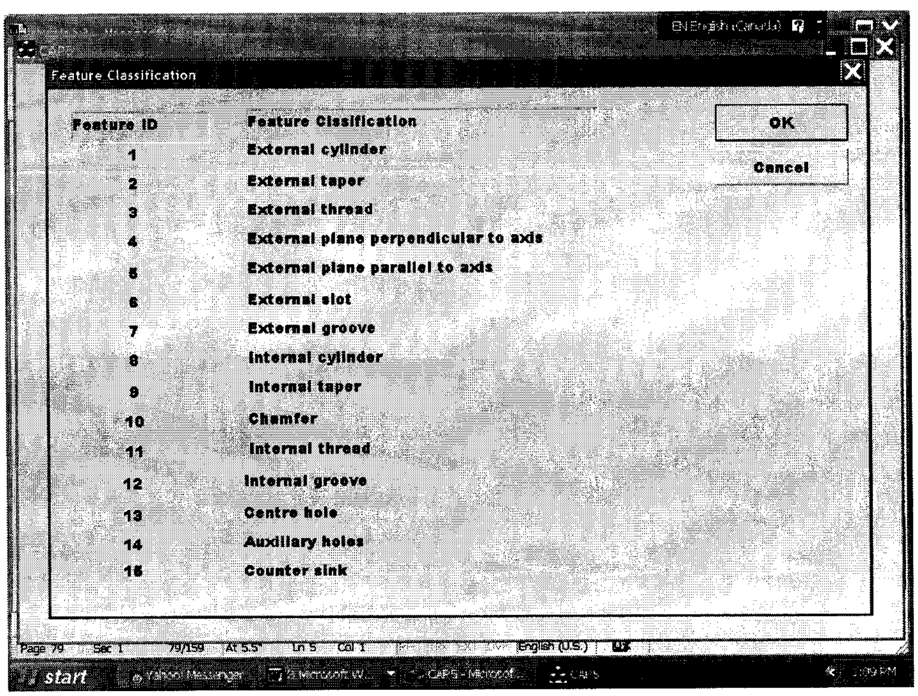


Figure 4.18. Feature Classification

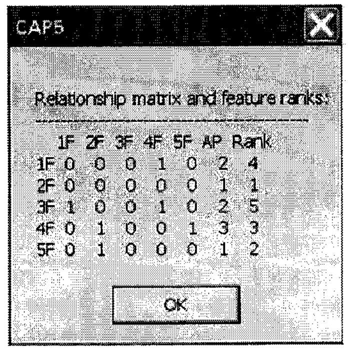


Figure 4.19. Feature Priority Matrix, Tool Approach Direction and Feature Rank

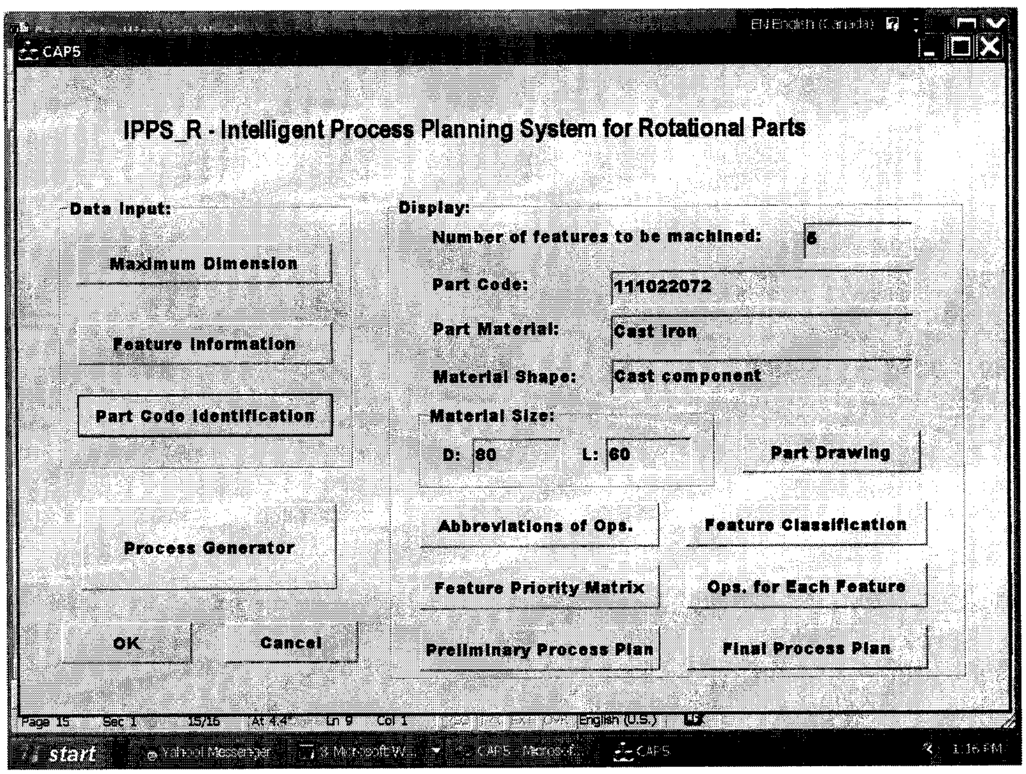
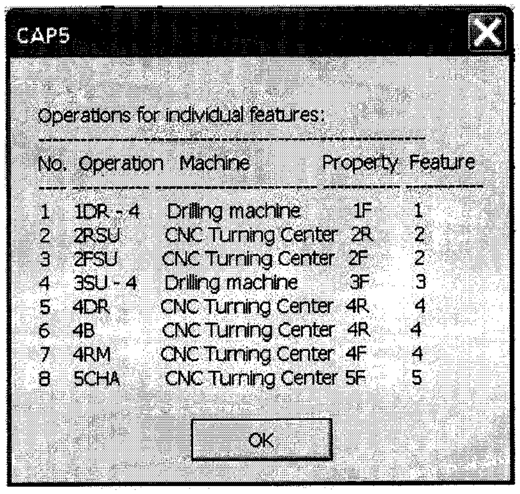


Figure 4.20. Part Code and Raw Stock Information

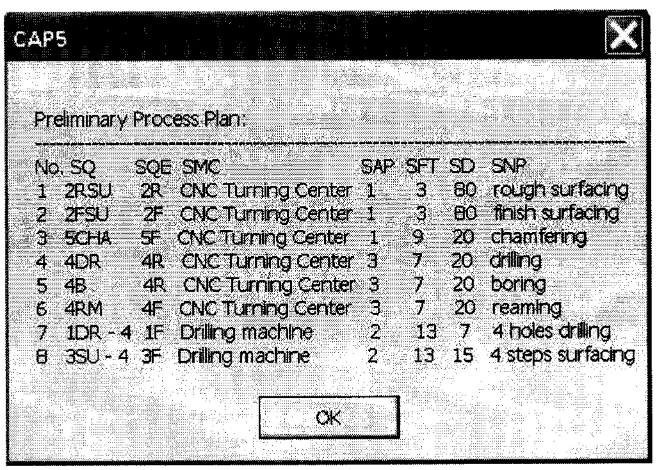

CAP5

Operations for individual features:

No.	Operation	Machine	Property	Feature
1	1DR - 4	Drilling machine	1F	1
2	2RSU	CNC Turning Center	2R	2
3	2FSU	CNC Turning Center	2F	2
4	3SU - 4	Drilling machine	3F	3
5	4DR	CNC Turning Center	4R	4
6	4B	CNC Turning Center	4R	4
7	4RM	CNC Turning Center	4F	4
8	5CHA	CNC Turning Center	5F	5

OK

Figure 4.21. Operations and Machines


CAP5

Preliminary Process Plan:

No.	SQ	SQE	SMC	SAP	SFT	SD	SNP
1	2RSU	2R	CNC Turning Center	1	3	80	rough surfacing
2	2FSU	2F	CNC Turning Center	1	3	80	finish surfacing
3	5CHA	5F	CNC Turning Center	1	9	20	chamfering
4	4DR	4R	CNC Turning Center	3	7	20	drilling
5	4B	4R	CNC Turning Center	3	7	20	boring
6	4RM	4F	CNC Turning Center	3	7	20	reaming
7	1DR - 4	1F	Drilling machine	2	13	7	4 holes drilling
8	3SU - 4	3F	Drilling machine	2	13	15	4 steps surfacing

OK

Figure 4.22. Preliminary Process Plan

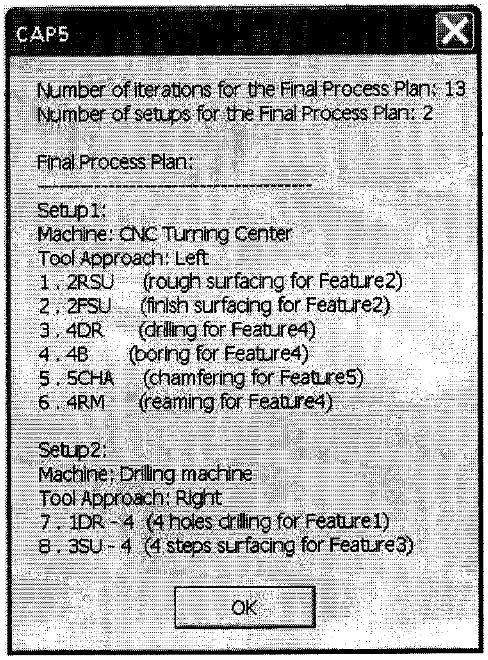


Figure 4.23. Final Process Plan

Chapter 5: Case Studies Using the IPPS_R System

The IPPS_R system is carefully tested by using real machining planning cases. The testing process is carried out in three stages: (1) verification of the functionalities of the whole system step by step (2) verification of the process plans generated by the IPPS_R system by comparing them with manual process plans available from the published literature, and (3) verification of process plans on the CAM software - MasterCAM V9.

In this chapter, the use and execution of the IPPS_R system are discussed with practical examples and demonstrations, and the results for the sample parts are further validated with simulation of processes and generation of CNC codes by utilizing MasterCAM.

5.1 Case Study One - Shaft

5.1.1 Process Plan Generated by the IPPS_R System

The sample component, shown in Figure 5.1, is a shaft with external screw threads. Before using the IPPS_R system, a feature-based part description form, shown in Table 5.1, has to be prepared by a user. In Table 5.1, the shaft is decomposed into 18 machining features. Each feature is described with its classification, main geometric sizes, accuracy and tool access direction, respectively. The material of the part and the relationships among the features are also presented in this table.

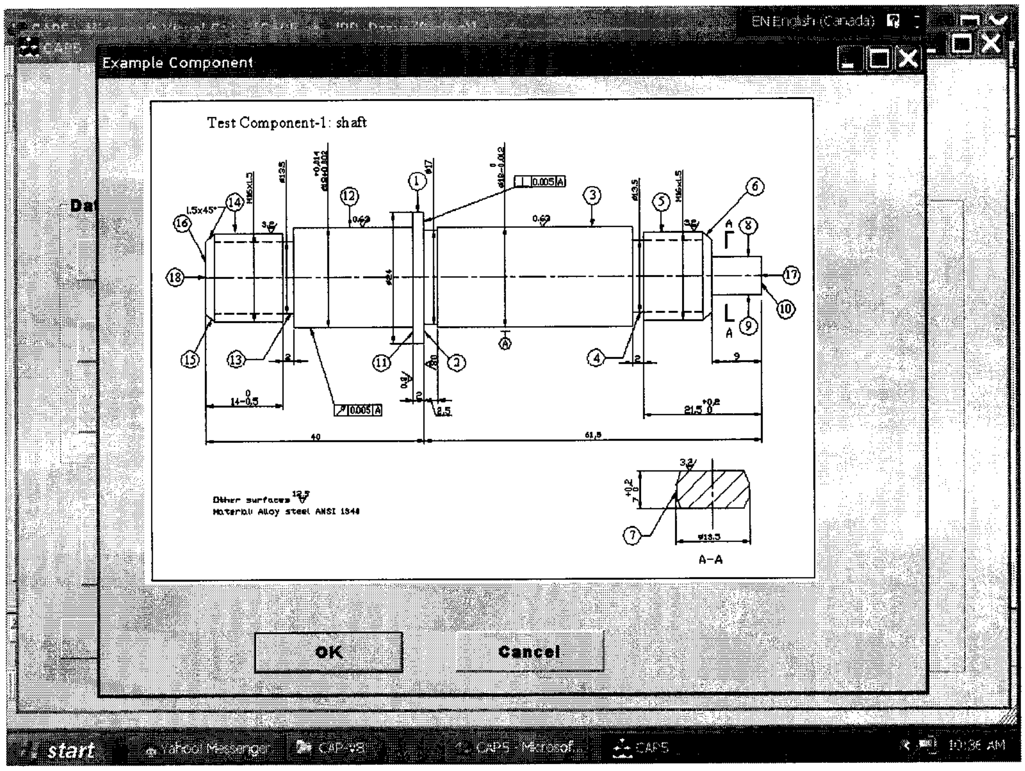


Figure 5.1. Sample Part - Shaft

Table 5.1. Part Description Form for the Shaft

Feature ID	Feature Classification	Length (mm)	Diameter (mm)	Tolerance Grade Number	Surface Finish Class	Precedent Feature	Tool Approach
F1	External cylinder	2	ϕ24	11	3		Both
F2	End face		Out. ϕ24 In. ϕ18	8	6	F3	Right
F3	External cylinder	38	ϕ18	6	9	F9	Right
F4	Ext. groove	2	ϕ13.5	11	3	F6	Right
F5	Ext. thread	12	M16×1.5	8	6	F4, F6	Right
F6	Chamfer		ϕ16×1×1			F7	Right
F7	External cylinder	9	ϕ13.5	11	3	F17	Right
F8	Ext. plane	9x3.5		8	6	F7, F14	Right
F9	Ext. plane	9x3.5		8	6	F7, F8	Left
F10	End Face		ϕ13.5			F1	Right
F11	End face		Out. ϕ24 In. ϕ18	7	8	F2	Left
F12	External cylinder	36	ϕ18	6	9	F3, F11	Left
F13	Ext. groove	2	ϕ13.5	11	3	F18	Left
F14	Ext. thread	14	M16×1.5	8	6	F13, F15	Left
F15	Chamfer		ϕ16×1×1	11	3	F13	Left
F16	End Face		ϕ16	11	3	F5	Left
F17	Centre hole			11	3	F10	Right
F18	Centre hole			11	3	F16	Left

Material: Alloy steel ANSI 1340
Material form: Forged
Other surfaces: Ra=12.5 (class: 3)
Note: For equivalent surface finish classes and tolerance grades to their respective values, please see Table 2.1 and Table 2.2. in Chapter 2

Information from Table 5.1 is inputted to the IPPS_R system through the user interface. A CAD drawing can also be pre-loaded into the system. Once the required information is inputted, the *Process Generation* sub-system can be started. Subsequently, the intermediate and final results are produced.

At the first stage, the *Code Generation module* is executed. An Opitz code is generated. Based upon the information on raw material form and shape, the size of the raw stock is calculated. The feature relationship matrix is constructed. The part code and raw stock information are shown in Table 5.2, and the feature relationship matrix is shown in Table 5.3.

Table 5.2. Part Code and Raw Stock Information

Part Code	Material Type	Stock Diameter (mm)	Stock Length (mm)
250203671	Forged steel	$\phi 29$	106

Table 5.3. Feature Relationship Matrix for the Shaft

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18
F1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F3	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
F4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
F5	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
F6	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
F7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
F8	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
F9	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
F10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F11	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F12	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
F13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
F14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
F15	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
F16	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
F17	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
F18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

After the part code and stock size are determined, the *Operation Generation module* identifies the possible operations for each feature according to its classification and size. Operations for each feature are generated by aggregating and defuzzying the values of the fuzzy membership functions based on the tolerance and surface finish classes of the feature. The possible operations for each feature of the shaft are listed in Figure 5.2.

No.	Operation	Machine	Features
1	1T	CNC Turning Center	F1
2	2RSU	CNC Turning Center	F2
3	2FSU	CNC Turning Center	F2
4	2ENG	External grinder	F2
5	3RT	CNC Turning Center	F3
6	3FT	CNC Turning Center	F3
7	3REG	External grinder	F3
8	3FEG	External grinder	F3
9	4EGV	CNC Turning Center	F4
10	5T	CNC Turning Center	F5
11	5ETT	CNC Turning Center	F5
12	6CHA	CNC Turning Center	F6
13	7T	CNC Turning Center	F7
14	8FM	Vertical miller	F8
15	9FM	Vertical miller	F9
16	10FSU	CNC Turning Center	F10
17	11RSU	CNC Turning Center	F11
18	11FSU	CNC Turning Center	F11
19	11ENG	External grinder	F11
20	12RT	CNC Turning Center	F12
21	12FT	CNC Turning Center	F12
22	12REG	External grinder	F12
23	12FEG	External grinder	F12
24	13EGV	CNC Turning Center	F13
25	14T	CNC Turning Center	F14
26	14ETT	CNC Turning Center	F14
27	15CHA	CNC Turning Center	F15
28	16FSU	CNC Turning Center	F16
29	17CDR	CNC Turning Center	F17
30	18CDR	CNC Turning Center	F18

Figure 5.2. Operations for Individual Features of the Shaft

The *Feature Priority Ranking module* ranks the features in processing order based on the feature relationship matrix algorithm developed in Chapter 3. Once the ranks of the features are determined, the *Preliminary Operation Sequencing module* rearranges the operations based on their ranks as well as machining technical constraints. Thus, a preliminary process plan, as shown in Figure 5.3, is produced, which is feasible to be implemented on machines but may not be efficient.

No.	Sequence	SQE.	Machine	AP.	FT.	FD	Operation Explanation
1	1T	1F	CNC Turning Center	3	0	24	turning
2	10FSU	10F	CNC Turning Center	1	3	13	surfacing
3	17CDR	17F	CNC Turning Center	1	12	0	center drilling (for set-up)
4	7T	7F	CNC Turning Center	1	0	13	turning
5	6CHA	6F	CNC Turning Center	1	9	16	chamfering
6	4EGV	4F	CNC Turning Center	1	6	13	external grooving
7	5T	5R	CNC Turning Center	1	2	16	turning
8	5ETT	5F	CNC Turning Center	1	2	16	turning external thread screw
9	16FSU	16F	CNC Turning Center	2	3	16	surfacing
10	18CDR	18F	CNC Turning Center	2	12	0	center drilling (for set-up)
11	13EGV	13F	CNC Turning Center	2	6	13	external grooving
12	15CHA	15F	CNC Turning Center	2	9	16	chamfering
13	14T	14R	CNC Turning Center	2	2	16	turning
14	14ETT	14F	CNC Turning Center	2	2	16	turning external thread screw
15	8FM	8F	Vertical miller	1	4	0	milling
16	9FM	9F	Vertical miller	2	4	0	milling
17	3RT	3R	CNC Turning Center	1	0	18	rough turning
18	3FT	3R	CNC Turning Center	1	0	18	finish turning
19	3REG	3S	External grinder	1	0	18	rough grinding external cylinder
20	3FEG	3F	External grinder	1	0	18	finish grinding external cylinder
21	2RSU	2R	CNC Turning Center	1	3	24	rough surfacing
22	2FSU	2R	CNC Turning Center	1	3	24	finish surfacing
23	2ENG	2F	External grinder	1	3	24	grinding end surface
24	11RSU	11R	CNC Turning Center	2	3	24	rough surfacing
25	11FSU	11R	CNC Turning Center	2	3	24	finish surfacing
26	11ENG	11F	External grinder	2	3	24	grinding end surface
27	12RT	12R	CNC Turning Center	2	0	18	rough turning
28	12FT	12R	CNC Turning Center	2	0	18	finish turning
29	12REG	12S	External grinder	2	0	18	rough grinding external cylinder
30	12FEG	12F	External grinder	2	0	18	finish grinding external cylinder

Note: SQE. - process abbreviation, the number indicates the feature identification code,
R: rough machining, S: semi-finish machining, F: finish machining
AP. - cutting tool approach direction
FT. - feature classification code
FD. - feature size (diameter)

Figure 5.3. Preliminary Process Plan of the Shaft based on both Geometric and Technical Constraints

Next, the preliminary process plan is grouped by the *Setup Selection module.* The setup groups are determined according to the tool approach directions and machines utilized when operations are performed. Only those operations, implemented on the same machine and with the same tool approach direction, can be grouped into one setup. The setups for the preliminary process plan of the shaft are shown in Figure 5.4.

```
--------------------------------------------------------------------
Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1   1T       (turning)
2   10FSU    (surfacing)
3   17CDR    (center drilling for set-up)
4   7T       (turning)
5   6CHA     (chamfering)
6   4EGV     (external grooving)
7   5T       (turning)
8   5ETT     (turning external thread screw)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
9   16FSU    (surfacing)
10  18CDR    (center drilling for set-up)
11  13EGV    (external grooving)
12  15CHA    (chamfering)
13  14T      (turning)
14  14ETT    (turning external thread screw)

Setup3:
Machine: Vertical miller
Tool Approach: Left
15  8FM      (milling)

Setup4:
Machine: Vertical miller
Tool Approach: Right
16  9FM      (milling)

Setup5:
Machine: CNC Turning Center
Tool Approach: Right
17  3RT      (rough turning)
18  3FT      (finish turning)
--------------------------------------------------------------------
```

Figure 5.4. Setup Groups for the Preliminary Process Plan of the Shaft

```
--------------------------------------------------------------------------
Setup6:
Machine: External grinder
Tool Approach: Right
19  3REG     (rough grinding external cylinder)
20  3FEG     (finish grinding external cylinder )

Setup7:
Machine: CNC Turning Center
Tool Approach: Right
21  2RSU     (rough surfacing)
22  2FSU     (finish surfacing)

Setup8:
Machine: External grinder
Tool Approach: Right
23  2ENG     (grinding end surface)

Setup9:
Machine: CNC Turning Center
Tool Approach: Left
24  11RSU    (rough surfacing)
25  11FSU    (finish surfacing)

Setup10:
Machine: External grinder
Tool Approach: Left
26  11ENG    (grinding end surface)

Setup11:
Machine: CNC Turning Center
Tool Approach: Left
27  12RT     (rough turning)
28  12FT     (finish turning)

Setup12:
Machine: External grinder
Tool Approach: Left
29  12REG    (rough grinding external cylinder)
30  12FEG    (finish grinding external cylinder)
--------------------------------------------------------------------------
```

Figure 5.4 (cont'd). Setup Groups for the Preliminary Process Plan of the Shaft

At the last stage, the *Sequence heuristic search module* is executed. The heuristic search process looks for all the possible process plans by the breadth-first search technique. The best process plan is obtained by comparing the number of setups for each feasible plan. Starting from the Preliminary Process Plan, the search takes 14 iterations to reach the final goal for the sample part. The starting plan has 12 setups and the final one has 6. The detailed search iterations are given in Appendix C. The final result is shown in Figure 5.5.

```
-------------------------------------------------------------------------
Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T        (turning for Feature1)
2 . 3RT       (rough turning for Feature3)
3 . 2RSU      (rough surfacing for Feature2)
4 . 2FSU      (finish surfacing for Feature2)
5 . 3FT       (finish turning for Feature3)
6 . 5T        (turning for Feature5)
7 . 10FSU     (surfacing for Feature10)
8 . 17CDR     (center drilling (for set-up) for Feature17)
9 . 7T        (turning for Feature7)
10. 6CHA      (chamfering for Feature6)
11. 4EGV      (external grooving for Feature4)
12. 5ETT      (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 11RSU     (rough surfacing for Feature11)
14. 11FSU     (finish surfacing for Feature11)
15. 12RT      (rough turning for Feature12)
16. 12FT      (finish turning for Feature12)
17. 14T       (turning for Feature14)
18. 16FSU     (surfacing for Feature16)
19. 18CDR     (center drilling (for set-up) for Feature18)
20. 13EGV     (external grooving for Feature13)
21. 15CHA     (chamfering for Feature15)
22. 14ETT     (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left
23. 8FM       (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right
24. 9FM       (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right
25. 3REG      (rough grinding external cylinder for Feature3)
26. 3FEG      (finish grinding external cylinder for Feature3)
27. 2ENG      (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG     (grinding end surface for Feature11)
29. 12REG     (rough grinding external cylinder for Feature12)
30. 12FEG     (finish grinding external cylinder for Feature12)
-------------------------------------------------------------------------
```

Figure 5.5. Final Process Plan of the Shaft

5.1.2 Verification of the Process Plan for the Shaft

To assess the feasibility of the process plan generated by the IPPS_R system, the process plan for the shaft is verified and simulated on MasterCAM9, which is a commercial computer-aided manufacturing software package. Operated in the Windows environment, MasterCAM can produce solid drawings, tool paths and CNC codes for turning, drilling and milling operations performed on CNC lathe and milling machines.

A CAD drawing of the shaft is first created in the CAD interface. Next, part setup, tool paths and operations are selected according to the process plan generated by the IPPS_R system. Each step of the operations is verified. Finally, the simulation of the process and the CNC codes for the shaft are created in the MasterCAM environment. The tool paths for the shaft are shown in Figure 5.6 and the simulation results are illustrated in Figure 5.7 and Figure 5.8. The CNC codes generated are listed in Appendix C, while Appendix D provides standard codes for NC programming.

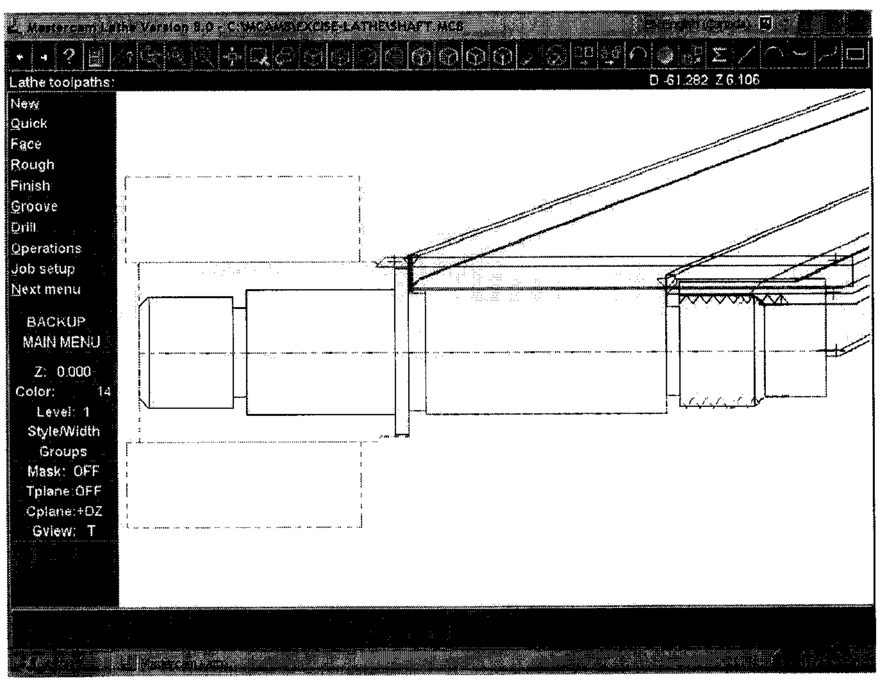


Figure 5.6. Tool Paths for the Shaft

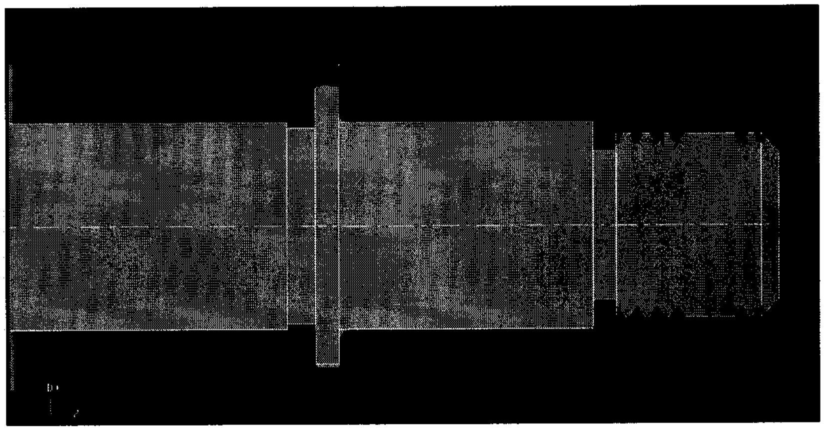


Figure 5.7. Final Turning Steps for the Shaft

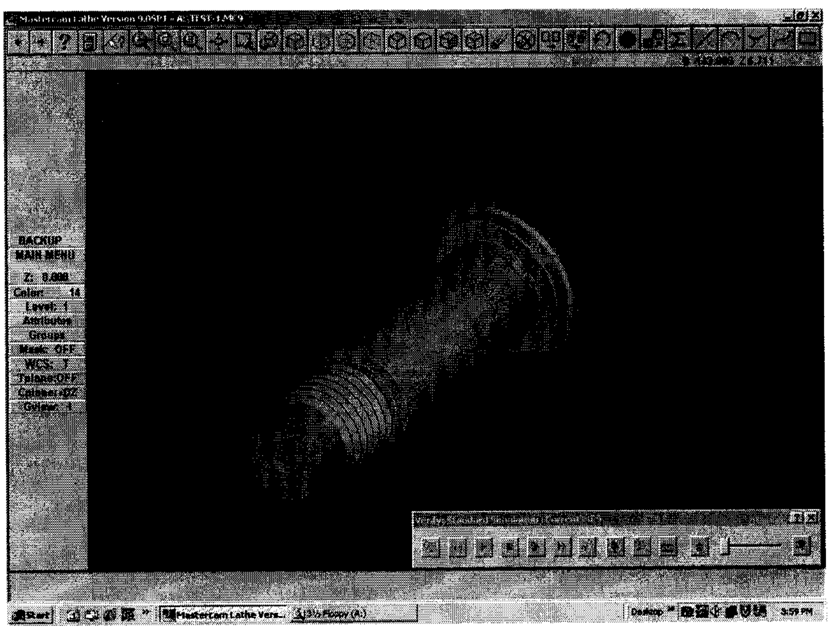


Figure 5.8. Simulation of the Turning Operations for the Shaft

The simulation results show that the process plans produced by the IPPS_R system are feasible and efficient. There are no conflicts among operation sequences. Notice that this verification has its limitations since only turning and milling operations can be simulated by utilizing MasterCAM tools.

5.2 Case Study Two – Valve Cover

5.2.1 Process Plan Generated by the IPPS_R System

The use of the IPPS_R system is illustrated through another sample part in this section. The sample part, Valve Cover (Halevi, 1980), is shown in Figure 5.9. Similarly, a part description form is prepared as shown in Table 5.4 based on the part drawing.

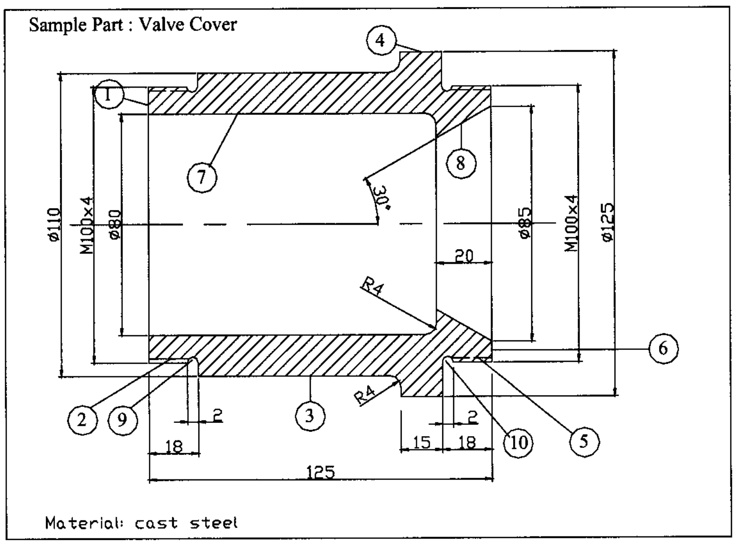


Figure 5.9. Sample Part – Valve Cover

Table 5.4. Part Description Form for the Valve Cover

Feature ID	Feature description	Length (mm)	Diameter (mm)	Tolerance	Precedent Features	Tool Approach
F1	End Face		ϕ100			Left
F2	External thread	16	M100×4		F9	Left
F3	External cylinder	74	ϕ110		F1	Left
F4	External cylinder	15	ϕ125		F2	Right
F5	External thread	16	M100×4		F10	Right
F6	End Face		ϕ100		F2, F4	Right
F7	Internal cylinder	105	ϕ80		F1, F3	Left
F8	Internal taper	20	ϕ85 taper: 30°		F6	Right
F9	External groove	2	2		F3	Left
F10	External groove	2	2		F5, F6	Right
Material: Carbon steel, heat-treated. Material form: Forged.						

The same procedure as used for the shaft is applied to the Valve Cover. After the feature data are inputted through the user interface, the system modules carry out functions of automated process planning. The intermediate and final results are shown through the User Interface. The part code, raw stock information and number of the features are given in Main Screen, as shown in Figure 5.10; the feature relationship matrix for the Valve Cover is given in Figure 5.11; and the possible operations for the Valve Cover are shown in Figure 5.12.

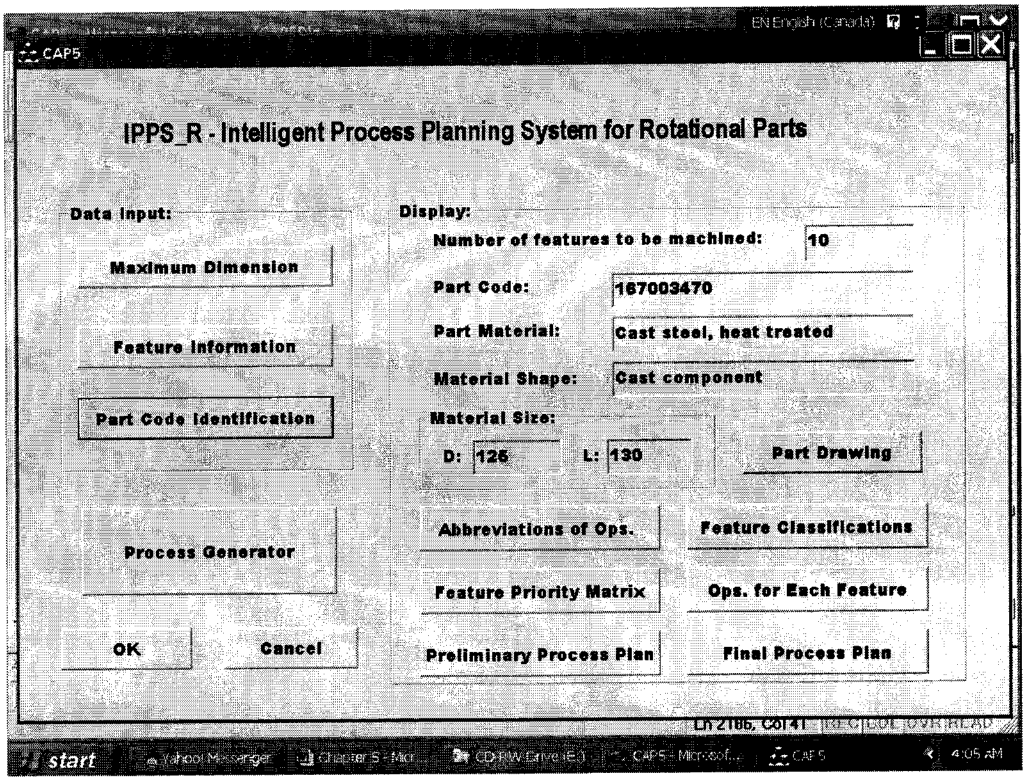
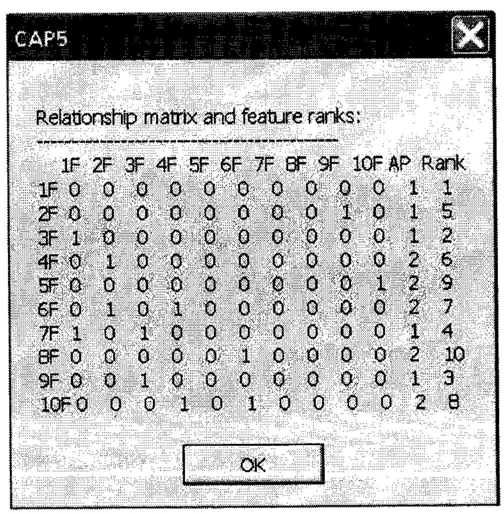
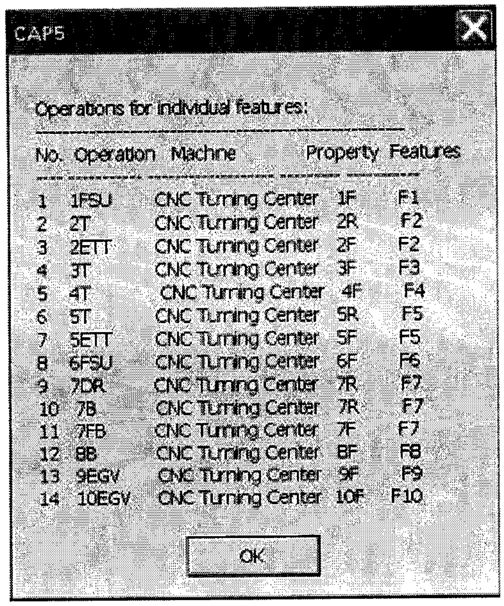


Figure 5.10. Part Code and Raw Stock Information for the Valve Cover



	1F	2F	3F	4F	5F	6F	7F	8F	9F	10F	AP	Rank
1F	0	0	0	0	0	0	0	0	0	0	1	1
2F	0	0	0	0	0	0	0	0	1	0	1	5
3F	1	0	0	0	0	0	0	0	0	0	1	2
4F	0	1	0	0	0	0	0	0	0	0	2	6
5F	0	0	0	0	0	0	0	0	0	1	2	9
6F	0	1	0	1	0	0	0	0	0	0	2	7
7F	1	0	1	0	0	0	0	0	0	0	1	4
8F	0	0	0	0	0	1	0	0	0	0	2	10
9F	0	0	1	0	0	0	0	0	0	0	1	3
10F	0	0	0	1	0	1	0	0	0	0	2	8

Figure 5.11. Feature Relationship Matrix for the Valve Cover



CAP5

Operations for individual features:

No.	Operation	Machine	Property	Features
1	1FSU	CNC Turning Center	1F	F1
2	2T	CNC Turning Center	2R	F2
3	2ETT	CNC Turning Center	2F	F2
4	3T	CNC Turning Center	3F	F3
5	4T	CNC Turning Center	4F	F4
6	5T	CNC Turning Center	5R	F5
7	5ETT	CNC Turning Center	5F	F5
8	6FSU	CNC Turning Center	6F	F6
9	7DR	CNC Turning Center	7R	F7
10	7B	CNC Turning Center	7R	F7
11	7FB	CNC Turning Center	7F	F7
12	8B	CNC Turning Center	8F	F8
13	9EGV	CNC Turning Center	9F	F9
14	10EGV	CNC Turning Center	10F	F10

OK

Figure 5.12. Possible Operations for the Valve Cover - Generated from the Operation Generation Module

After the *Feature Priority Ranking module* produces the ranking of the features, operations are sequenced through the *Preliminary Operation Sequencing module.* A preliminary process plan satisfying geometric and technical constraints is created. The preliminary process plan for the Valve Cover is presented in Figure 5.13.

No.	SQ	SQE	MACHINE	AP	FT	SD	SPECIFICATION
1	1FSU	1F	CNC Turning Center	1	3	125	surfacing
2	3T	3F	CNC Turning Center	1	0	110	turning
3	9EGV	9F	CNC Turning Center	1	6	96	external grooving
4	7DR	7R	CNC Turning Center	1	7	80	drilling
5	7B	7R	CNC Turning Center	1	7	80	boring
6	7FB	7F	CNC Turning Center	1	7	80	finish boring
7	2T	2R	CNC Turning Center	1	2	100	turning
8	2ETT	2F	CNC Turning Center	1	2	100	tapping external thread
9	4T	4F	CNC Turning Center	2	0	125	turning
10	6FSU	6F	CNC Turning Center	2	3	125	surfacing
11	10EGV	10F	CNC Turning Center	2	6	96	external grooving
12	5T	5R	CNC Turning Center	2	2	100	turning
13	5ETT	5F	CNC Turning Center	2	2	100	tapping external thread
14	8B	8F	CNC Turning Center	2	8	85	boring internal taper

Where,
SQ - Abbreviation of sequence
SQE - Operation properties - rough, semi-finish or finish machining
AP - Tool access direction
FT - Feature type identification number
SD - Feature's diameter

Figure 5.13. Preliminary Process Plan for the Valve Cover

The *Setup Selection module* groups operations and produces setup plans by considering tool approach directions and machines utilized. Based on the preliminary process plan, the *Sequence heuristic search module* produces the final process plan for the sample part. Subject to both geometric constraints and technical constraints of the part, the module searches the process plan with the least number of setups by using the breadth-first search technique. The search takes four iterations to reach the final process plan. As a result, the heuristic solution is given in Figure 5.14.

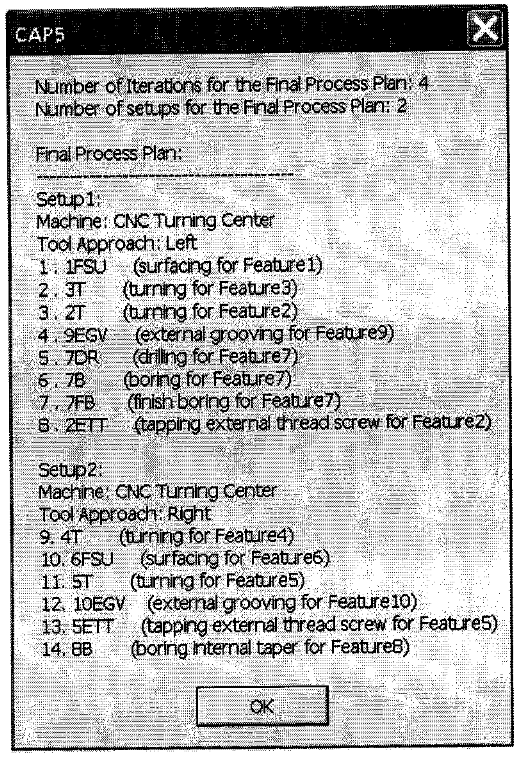


Figure 5.14. Final Process Plan for the Valve Cover

5.2.2 Verification of the Process Plan by Utilizing CAD/CAM Tools

The goal of the IPPS_R system is to create process plans for rotational parts automatically. These process plans should satisfy both geometrical and technical requirements. They are the most efficient plans characterized with the least machining time at certain cutting conditions. To reach the goal of the research, several sample parts are tested in the system and automated process plans are generated.

To assess the feasibility of the process plans produced by the IPPS_R system, the process plan for the Valve Cover is verified by utilizing SolidWorks Tool, as shown in Figure 5.15. Furthermore, it is verified and simulated step by step in the MasterCAM environment. The tool paths are verified and simulated, as shown in Figure 5.16 to Figure 5.18. The CNC codes for processing the Valve Cover are generated, as listed in Appendix E. The simulation results show that the process plans generated by the IPPS_R system are feasible and efficient. There are no conflicts among operation sequences.

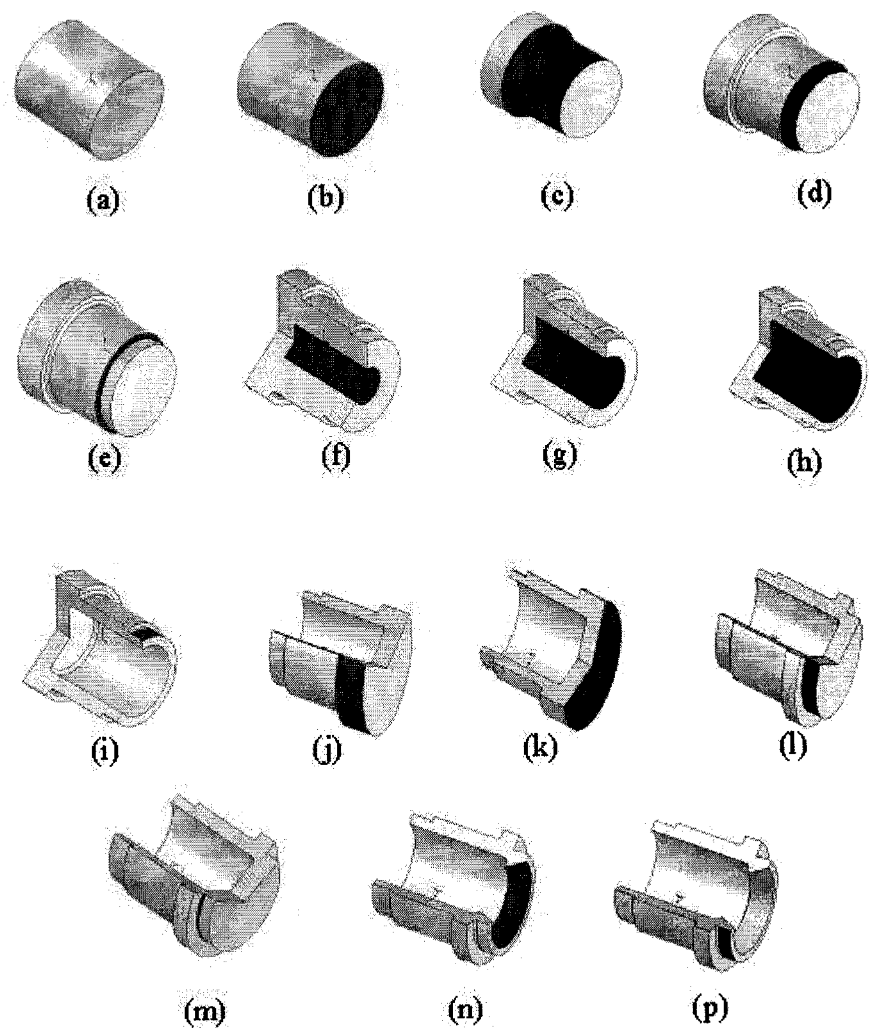


Figure 5.15. Successive modification of the Valve Cover
(a) raw work-piece; (b) facing F1; (c) turning F3; (d) turning F2; (e) grooving F9; (f) drilling hole F7; (g) boring F7; (h) finish boring F7; (i) tapping thread F2; (j) turning F4; (k) facing F6; (l) turning F5; (m) grooving F10; (n) tapping thread F5; and (p) boring internal taper F8.

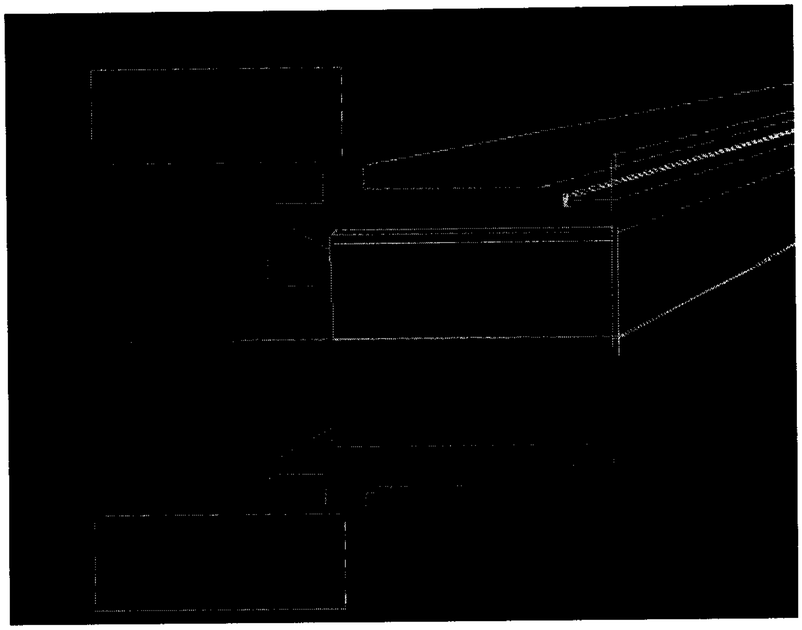


Figure 5.16. Tool Paths for the Valve Cover

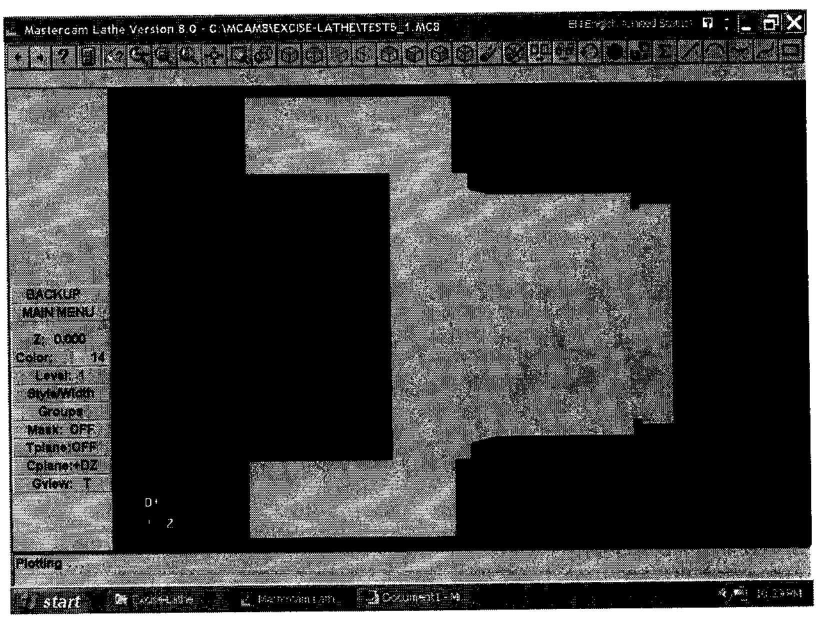


Figure 5.17. One Operation Step for the Valve Cover

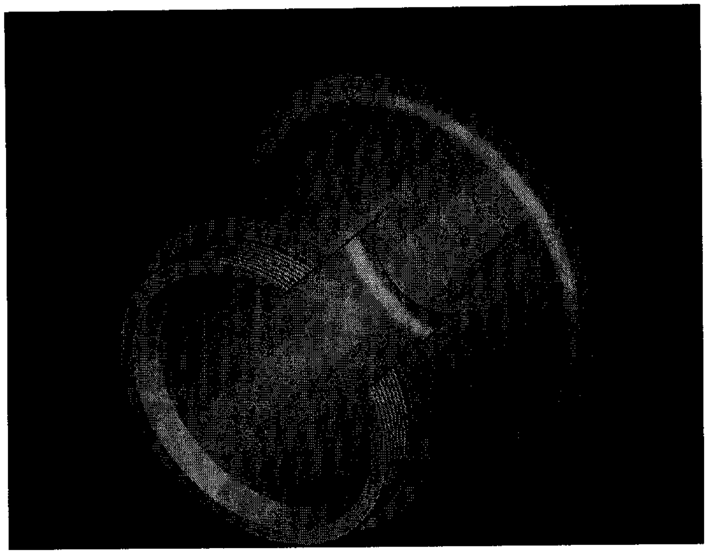


Figure 5.18. Simulation Result for the Valve Cover

5.2.3 Verification through Comparison

Another evaluation approach is to compare the process plans generated by the IPPS_R system with those produced by human process planners manually. Table 5.5 gives process plans developed by four different planners for the Valve Cover. Obviously, diversities exist among the four plans, even in the selection of raw material dimension. But there are similarities among those plans. First, they apply similar machine resources. Next, they use similar machining approaches, although there are differences among the operation sequences. Of course, they are feasible process plans, although not all are most economic. The exact comparison is hard to make between different plans, since the most plans come from planners' own experiences as well as available machining resources.

The process plan generated by the IPPS_R system is carefully compared in the setups, operation selections and machine resources applications. One of the limitations in comparing plans is that cutting parameters are not considered.

Table 5.5. Process Plans Prepared by Four Human Process Planners

Operation number	Process planner			
	One	Two	Three	Four
Raw material	130ϕ × 130	130ϕ × 130	130ϕ × 128	127ϕ × 127
10			Chuck on drill press	
20			Drill 75ϕ	
30	Chuck on lathe	Chuck on lathe	Chuck on lathe	Chuck on lathe
40	Face cut	Face cut	Face cut	Drill 30ϕ
50	Ext. cut 114ϕ	Drill 20ϕ	Ext. cut 110ϕ	Bore 60ϕ
60	Ext. cut 128ϕ	Drill 38ϕ	Ext. cut 100ϕ	Cut 110ϕ
70	Ext. cut 105ϕ	Drill 55ϕ	Thread cut	Cut 100ϕ
80	Drill 25ϕ	Bore 63ϕ	Bore 80ϕ	Face cut
90	Drill 40ϕ	Bore 80ϕ		Bore 80ϕ
100	Drill 60ϕ	Ext. cut 110ϕ		Thread cut
110	Bore 80ϕ	Ext. cut 100ϕ		
120	Cut 125ϕ	Thread cut		
130	Cut 110ϕ			
140	Cut 100ϕ			
150	Thread cut			
160	Chuck	Chuck	Chuck	Chuck
170	Face cut	Face cut	Face cut	Cut 125ϕ
180	Bore cone	Cut 125ϕ	Cut 125ϕ	Cut 100ϕ
190	Cut 100ϕ	Cut 100ϕ	Cut 100ϕ	Face cut
200	Thread cut	Thread cut	Thread cut	Thread cut
210		Bore cone	Bore cone	Bore cone
220		Burr		Burr

Source: Halevi,G., 1980. *The Role of Computers in Manufacturing Processes,* p292, Wiley, New York, USA.

The IPPS_R system is tested with two sample cases, and the results are verified using CAD/CAM tools. The test results show that the process plans generated by the IPPS_R system are consistent with manufacturing practices by computer simulation. Due to the limitation of current computer tools, the system is not integrated with automated feature recognition.

Chapter 6: Conclusions and Future Research

6.1 Summary of the Contributions

The IPPS_R system has been developed for automatically creating process plans for rotational parts. The main contributions of this thesis can be summarized as follows:

- An automated process planning system for rotational parts has been developed by means of the generative approach. The main steps involved in developing the IPPS_R system are: part representation, operation generation, machine selection, preliminary operation sequencing, setup selection and sequence heuristic search. The Opitz coding system and machining features are employed for part representation and provide an easy way to describe a component. Fuzzy set and fuzzy logic techniques are applied to generate and to select machining operations. The feature relationship matrix is utilized for sequencing operations. Setup grouping and selection are based on tool approach directions and required machines. Sequence heuristic search is achieved by utilizing the breadth-first search method based on the least number of setups.

- The IPPS_R system has been developed and implemented in Microsoft Visual C++ 6.0 on a personal computer. The system provides a highly intuitive user interface that consists of dialog boxes, dialog sheets and control elements. The IPPS_R system can be operated by a user without any special computer software background.

- Based on the accuracy and surface quality requirements, a fuzzy logic approach has been developed to generate and select the operation for machining a feature. Hence, it is not necessary to build a high volume of machining databases in the computer.

- Based on the feature relationship matrix, a method has been developed for ranking features in terms of processing priority. Moreover, a procedure has been developed to group operations with the same tool approach direction and machine resource. These procedures play fundamental roles in sequencing operations and optimizing operation sequences.

- An operation sequence heuristic search module based on the breadth-first search technique has been developed to heuristically search a process plan with the minimum number of setups.

- Process plans for two sample parts have been generated by the IPPS_R system. The process plans generated have been verified and simulated by using CAD/CAM tools. Based on the process plans produced by the IPPS_R system, CNC codes are generated.

6.2 Future Research

Based on the work presented in this thesis, below are some possible directions for future research.

- The IPPS_R system is limited to rotational parts without deviation. However, it can be extended to prismatic parts or other non-rotational parts through increasing the number of the feature classifications to be manipulated.

- CAPP is the link between CAD and CAM. Current process planning systems cannot convert a CAD drawing to CAPP inputs directly. A transformation software system is required to carry out the task. Due to the lack of graphic transformation software, the IPPS_R system can not convert CAD drawings to required part description data.

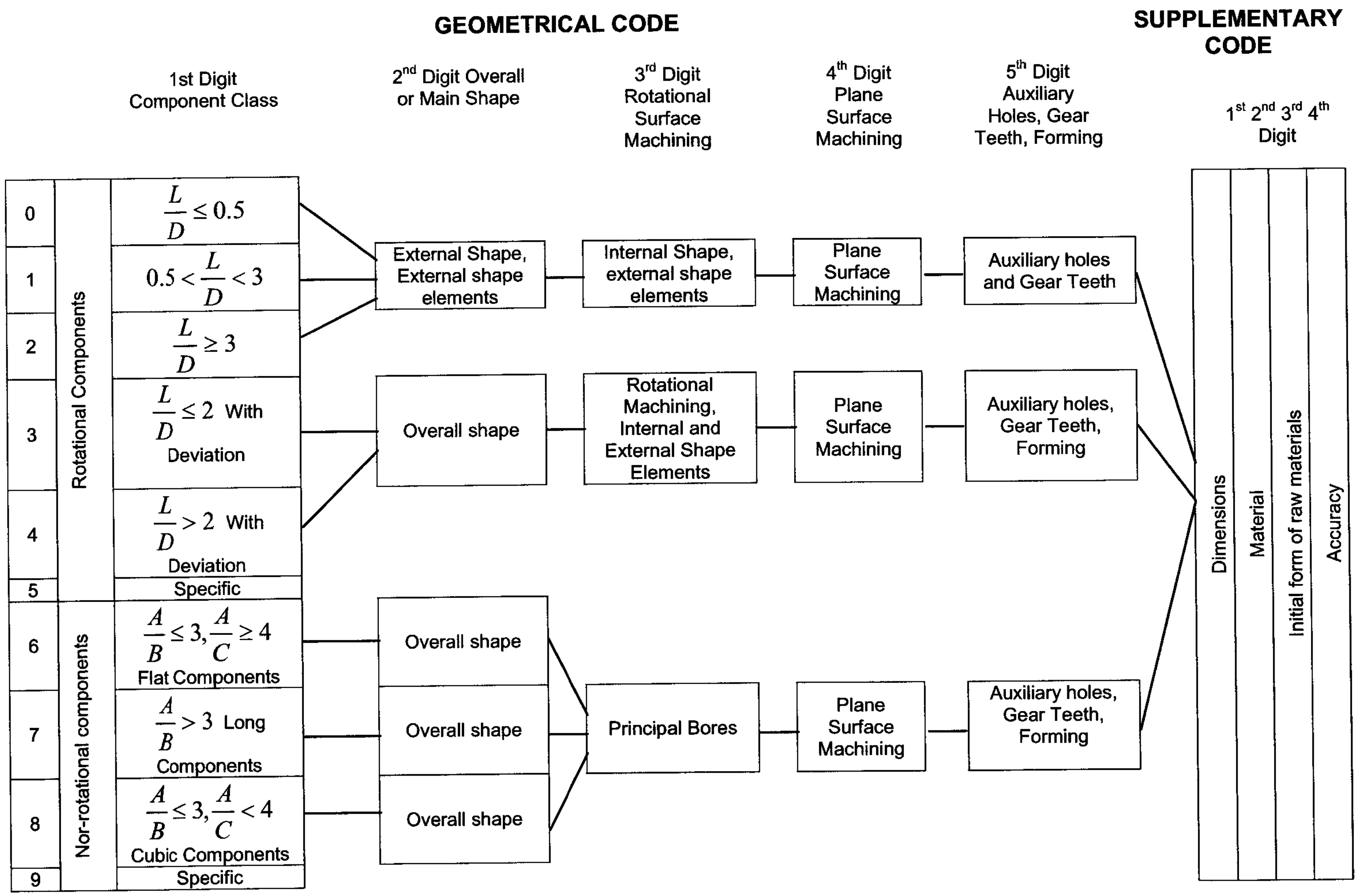
- Knowledge bases for process capabilities, machining resources and cutting conditions can be extended. Consideration of cutting parameters is needed. heuristic search of process plans can be extended to consider both least number of setups and optimal cutting conditions.

- Metal cutting experiments are needed to validate and enhance the practicality of the system.

Appendices

Appendix A: Opitz Code System

The completed Optiz classification system (Opitz, 1970) is given in this Appendix.


GEOMETRICAL CODE
SUPPLEMENTARY CODE
1st Digit Component Class
2nd Digit Overall or Main Shape
3rd Digit Rotational Surface Machining
4th Digit Plane Surface Machining
5th Digit Auxiliary Holes, Gear Teeth, Forming
1st 2nd 3rd 4th Digit
0
1
2
3
4
5
6
7
8
9
Rotational Components
Nor-rotational components
$\frac{L}{D} \leq 0.5$
$0.5 < \frac{L}{D} < 3$
$\frac{L}{D} \geq 3$
$\frac{L}{D} \leq 2$ With Deviation
$\frac{L}{D} > 2$ With Deviation
Specific
$\frac{A}{B} \leq 3, \frac{A}{C} \geq 4$ Flat Components
$\frac{A}{B} > 3$ Long Components
$\frac{A}{B} \leq 3, \frac{A}{C} < 4$ Cubic Components
Specific
External Shape, External shape elements
Overall shape
Overall shape
Overall shape
Overall shape
Internal Shape, external shape elements
Rotational Machining, Internal and External Shape Elements
Principal Bores
Plane Surface Machining
Plane Surface Machining
Plane Surface Machining
Auxiliary holes and Gear Teeth
Auxiliary holes, Gear Teeth, Forming
Auxiliary holes, Gear Teeth, Forming
Dimensions
Material
Initial form of raw materials
Accuracy

GEOMETRICAL CODE

1st Digit			2nd Digit				3rd Digit			4th Digit		5th Digit		
Component Class			External Shape, external shape elements				Internal Shape, internal shape elements			Plane Surface Machining		Auxiliary Hole(s) and Gear Teeth		
0	Rotational Components	$\frac{L}{D} \le 0.5$	0	Smooth, no shape elements			0	Without through bore, blind hole		0	No surface machining	0	no gear teeth	No auxiliary hole(s)
1		$0.5 < \frac{L}{D} < 3$	1	Stepped to one end	No shape elements		1	Smooth or stepped to one End	No shape elements	1	External plane surface and/or surface curved in one direction	1		Axial hole(s) not related by a drilling pattern
2		$\frac{L}{D} \ge 3$	2		Or smooth	With screw thread	2		With screw thread	2	External plane surfaces related to one another by graduation around a circle	2		Axial hole(s) related by a drilling pattern
			3			With screw thread	3		With screw thread	3	External groove and/or slot	3		radial hole(s) not related by a drilling pattern
			4	Stepped to both ends (multiple increases)		No shape elements	4	Stepped to both ends (multiple increases)	No shape elements	4	External spline and/or Polygon	4		Holes axial and/or radial and/in other directions, not related
			5			With screw thread	5		With screw thread	5	External plane surface and/or slot and/or groove, spline	5		Holes axial and/or radial and/in other directions related by drilling pattern
			6			With functional groove	6		With functional groove	6	Internal groove and/or slot	6	With gear teeth	Spur gear teeth
			7			Functional taper	7	Functional taper		7	Internal plane surface and/or groove	7		Bevel gear teeth
			8			Operating thread	8	Operating thread		8	External and Internal Spline and/or Polygon	8		Other gear teeth
			9			Others (>10 functional diameters)	9	Others (>10 functional diameters)		9	Others	9		Others

GEOMETRICAL CODE

1st Digit			2nd Digit			3rd Digit			4th Digit		5th Digit				
Component Class			Overall Shape			Rotational Machining			Plane Surface Machining		Auxiliary Hole(s), Gear Teeth, Forming				
	Rotational Components		0		Hexagonal bar	0		No rotational machining	0	No surface machining	0	no gear teeth			No auxiliary hole(s), gear teeth and forming
	Rotational Components		1	Around one Axis No Segments	Square or other regular Polygonal section	1	External Shape	No shape elements	1	External plane surface and/or surface curved in one direction	1	no gear teeth	No forming, no gear teeth		Axial hole(s) not related by a drilling pattern
	Rotational Components		2	Around one Axis No Segments	Symmetrical cross-section producing no unbalance	2	External Shape	With screw thread	2	Ext. plane surfaces related to one another by graduation around a circle	2	no gear teeth	No forming, no gear teeth		hole(s) axial and/or radial and/or in other directions, not related
3	Rotational Components	$\frac{L}{D} \leq 2$ With Deviation	3	Around one Axis No Segments	Cross-sections other than 0 to 2	3	Internal Shape	With screw thread	3	External groove and/or slot	3	no gear teeth	No forming, no gear teeth	Related by a drilling pattern	Axial holes
4	Rotational Components	$\frac{L}{D} > 2$ With Deviation	4		Segments after rotational machining	4	Internal Shape	Stepped towards one or both ends (Multiple increases)	4	External spline and/or Polygon	4	no gear teeth	No forming, no gear teeth	Related by a drilling pattern	Holes axial and/or radial and/in other directions
			5		Segments before rotational machining	5	Internal Shape	With screw thread	5	External plane surface and/or slot and/or groove, spline	5	no gear teeth	Forming, no gear teeth		Formed, no auxiliary holes
			6	Around more than one Axis	Rotational components with curved axis	6	Ext. and Int. Shape	Machined	6	Internal groove and/or slot	6	With gear teeth	Forming, no gear teeth		Formed, with auxiliary holes
			7	Around more than one Axis	Rotational Components with two or more parallel axes	7	Ext. and Int. Shape	Screw thread(s)	7	Internal plane surface and/or groove	7	With gear teeth			Gear teeth, no auxiliary hole(s)
			8	Around more than one Axis	Rotational components with intersecting axes	8		External Shape Elements	8	External and Internal Spline and/or slot and/or groove	8	With gear teeth			Gear teeth, with auxiliary hole(s)
			9		Others	9		Others Shape Elements	9	Other	9	With gear teeth			Other

GEOMETRICAL CODE

1st Digit			2nd Digit	3rd Digit	4th Digit	5th Digit
Component Class				Reserved for firm's own classification		
	Rotational Components					
5		Specific Rotational Components				

GEOMETRICAL CODE

1st Digit — 2nd Digit

Component Class				Overall Shape	
		0		Rectangular	
		1	Plane	Rectangular, with one deviation (Right Angle or Triangular)	
		2	Plane	Rectangular with circular deviation	
		3	Plane	With screw thread	
		4		Any flat shape other than o to 3	
		5		Flat components, rectangular or right angled with small deviations due to casting, welding, forming	
6	$\frac{A}{B} \leq 3, \frac{A}{C} \geq 4$ Flat Components	6		Flat components, round or of any shape other than position 5	
		7		Flat components regularly arched or dished	
		8		Flat components irregularly arched or dished	
		9		Others	

GEOMETRICAL CODE

1st Digit			2nd Digit			
Component Class			External Shape, external shape elements			
			0	Shape Axis-Straight	Uniform Cross-Section	Rectangular
			1			Rectangular with one deviation (Right Angle or Triangular)
			2			Any cross-section other than 0 or 1
			3		Varying Cross-Section	Rectangular
			4			Rectangular with one deviation (Right Angle or Triangular)
			5			Any cross-section other than 3 and 4
6	Non-rotational components		6	Shape Axis Curved (bent)		Rectangular, angular and other cross-sections
7		$\frac{A}{B} > 3$ Long Components	7			Formed component
			8			Formed component with deviations in the main axis
			9			Others

GEOMETRICAL CODE

1st Digit			2nd Digit			3rd Digit		4th Digit		5th Digit		
Component Class			Overall shape			Principal bore, rotational surface machining		Plane Surface Machining		Auxiliary Hole(s), Forming, Gear Teeth		
			0	Block and Block-like components	Rectangular	0	No rotational machining or bore(s)	0	No surface machining	0		No auxiliary holes, gear teeth and forming
			1	Block and Block-like components	Rectangular with deviations (Right Angle or Triangular	1	One principal bore, smooth	1	Functional chamfers (e.g. welding prep.)	1	Mp gear teeth, no forming	Holes drilled in one direction only
			2	Block and Block-like components	Compounded of Rectangular Prisms	2	One principal bore stepped to one or both ends	2	One plane surface	2	Mp gear teeth, no forming	Holes drilled in more than one direction
			3	Block and Block-like components	Components with a mounting or locating surface and principal bore	3	One principal bore with shape elements	3	Stepped plane surfaces	3	Mp gear teeth, no forming; Related by a drilling pattern	Holes drilled in one direction only
			4	Block and Block-like components	Components with a mounting or locating surface, principal bore with dividing surface	4	Two principal bores, parallel	4	Stepped plane surfaces at right angles, inclined and/or opposite	4	Mp gear teeth, no forming; Related by a drilling pattern	Holes drilled in more than one direction
			5	Block and Block-like components	Components other than 0 to 4	5	Several principal bores, parallel	5	Groove and/or Slot	5	Forming, no gear teeth	Formed, no auxiliary holes
	Non-rotational components		6	Box and Box-like components; Not split	Approximate or compounded of rectangular prisms	6	Several principal bores, other than parallel	6	Groove and/or Slot and 4	6	Forming, no gear teeth	Formed, with auxiliary holes
	Non-rotational components		7	Box and Box-like components; Not split	Components other than 6	7	Machined annular surfaces, annular grooves	7	Curved Surface	7		Gear teeth, no auxiliary hole(s)
8	Non-rotational components	$\frac{A}{B} \le 3, \frac{A}{C} < 4$ Cubic Components	8	Box and Box-like components; Split	Approximate or compounded of rectangular prisms	8	7 + principal bore(s)	8	Guide Surfaces	8		Gear teeth, with auxiliary hole(s)
	Non-rotational components		9	Box and Box-like components; Split	Components other than 8	9	Others	9	Others	9		Others

GEOMETRICAL CODE

1st Digit			2nd Digit	3rd Digit	4th Digit	5th Digit
Component Class				Reserved for firm's own classification		
	Non-rotational components					
9		Specific Non-rotational Components				

Appendix B: Heuristic Search Process for the Shaft

The process of searching all the possible process plans is presented for the sample component shaft. The search process utilizes the breadth-first search technique and compares the number of setups in each feasible plan. The plan(s) with the minimum number of setups is (are) considered to be optimal.

Iteration 1: Setup plan for Preliminary Process Plan of the Shaft

```
Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1    1T        (turning)
2    10FSU     (surfacing)
3    17CDR     (center drilling for set-up)
4    7T        (turning)
5    6CHA      (chamfering)
6    4EGV      (external grooving)
7    5T        (turning)
8    5ETT      (turning external thread screw)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
9    16FSU     (surfacing)
10   18CDR     (center drilling for set-up)
11   13EGV     (external grooving)
12   15CHA     (chamfering)
13   14T       (turning)
14   14ETT     (turning external thread screw)

Setup3:
Machine: Vertical miller
Tool Approach: Left
15   8FM       (milling)

Setup4:
Machine: Vertical miller
Tool Approach: Right
16   9FM       (milling)

Setup5:
Machine: CNC Turning Center
Tool Approach: Right
17   3RT       (rough turning)
18   3FT       (finish turning)

Setup6:
Machine: External grinder
Tool Approach: Right
19   3REG      (rough grinding external cylinder)
20   3FEG      (finish grinding external cylinder )
```

Setup7:
Machine: CNC Turning Center
Tool Approach: Right
21 2RSU (rough surfacing)
22 2FSU (finish surfacing)

Setup8:
Machine: External grinder
Tool Approach: Right
23 2ENG (grinding end surface)

Setup9:
Machine: CNC Turning Center
Tool Approach: Left
24 11RSU (rough surfacing)
25 11FSU (finish surfacing)

Setup10:
Machine: External grinder
Tool Approach: Left
26 11ENG (grinding end surface)

Setup11:
Machine: CNC Turning Center
Tool Approach: Left
27
28 12FT (finish turning)

Setup12:
Machine: External grinder
Tool Approach: Left
29 12REG (rough grinding external cylinder)
30 12FEG (finish grinding external cylinder)

Number of setups for Iteration1: 12

Iteration 2:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 10FSU (surfacing for Feature10)
3 . 17CDR (center drilling (for set-up) for Feature17)
4 . 7T (turning for Feature7)
5 . 6CHA (chamfering for Feature6)
6 . 5T (turning for Feature5)
7 . 4EGV (external grooving for Feature4)
8 . 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
9 . 16FSU (surfacing for Feature16)
10. 18CDR (center drilling (for set-up) for Feature18)

11. 13EGV (external grooving for Feature13)
12. 14T (turning for Feature14)
13. 15CHA (chamfering for Feature15)
14. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left
15. 8FM (milling for Feature8)

Setup4:
Machine: CNC Turning Center
Tool Approach: Right
16. 3RT (rough turning for Feature3)
17. 3FT (finish turning for Feature3)

Setup5:
Machine: Vertical miller
Tool Approach: Right
18. 9FM (milling for Feature9)

Setup6:
Machine: External grinder
Tool Approach: Right
19. 3REG (rough grinding external cylinder for Feature3)

Setup7:
Machine: CNC Turning Center
Tool Approach: Right
20. 2RSU (rough surfacing for Feature2)
21. 2FSU (finish surfacing for Feature2)

Setup8:
Machine: External grinder
Tool Approach: Right
22. 3FEG (finish grinding external cylinder for Feature3)

Setup9:
Machine: CNC Turning Center
Tool Approach: Left
23. 11RSU (rough surfacing for Feature11)
24. 11FSU (finish surfacing for Feature11)

Setup10:
Machine: External grinder
Tool Approach: Right
25. 2ENG (grinding end surface for Feature2)

Setup11:
Machine: CNC Turning Center
Tool Approach: Left
26. 12RT (rough turning for Feature12)
27. 12FT (finish turning for Feature12)

Setup12:
Machine: External grinder
Tool Approach: Left

28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration2: 12

Iteration 3:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 10FSU (surfacing for Feature10)
3 . 17CDR (center drilling (for set-up) for Feature17)
4 . 7T (turning for Feature7)
5 . 5T (turning for Feature5)
6 . 6CHA (chamfering for Feature6)
7 . 4EGV (external grooving for Feature4)
8 . 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
9 . 16FSU (surfacing for Feature16)
10. 18CDR (center drilling (for set-up) for Feature18)
11. 14T (turning for Feature14)
12. 13EGV (external grooving for Feature13)
13. 15CHA (chamfering for Feature15)
14. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: CNC Turning Center
Tool Approach: Right
15. 3RT (rough turning for Feature3)
16. 3FT (finish turning for Feature3)

Setup4:
Machine: Vertical miller
Tool Approach: Left
17. 8FM (milling for Feature8)

Setup5:
Machine: Vertical miller
Tool Approach: Right
18. 9FM (milling for Feature9)

Setup6:
Machine: CNC Turning Center
Tool Approach: Right
19. 2RSU (rough surfacing for Feature2)
20. 2FSU (finish surfacing for Feature2)

Setup7:
Machine: External grinder
Tool Approach: Right
21. 3REG (rough grinding external cylinder for Feature3)

Setup8:
Machine: CNC Turning Center
Tool Approach: Left
22. 11RSU (rough surfacing for Feature11)
23. 11FSU (finish surfacing for Feature11)

Setup9:
Machine: External grinder
Tool Approach: Right
24. 3FEG (finish grinding external cylinder for Feature3)

Setup10:
Machine: CNC Turning Center
Tool Approach: Left
25. 12RT (rough turning for Feature12)
26. 12FT (finish turning for Feature12)

Setup11:
Machine: External grinder
Tool Approach: Right
27. 2ENG (grinding end surface for Feature2)

Setup12:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)
I=14 J=7

Number of setups for Iteration3: 12

Iteration 4:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 10FSU (surfacing for Feature10)
3 . 17CDR (center drilling (for set-up) for Feature17)
4 . 5T (turning for Feature5)
5 . 7T (turning for Feature7)
6 . 6CHA (chamfering for Feature6)
7 . 4EGV (external grooving for Feature4)
8 . 5ETT (turning external thread screw for Feature5)
9 . 3RT (rough turning for Feature3)
10. 3FT (finish turning for Feature3)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
11. 16FSU (surfacing for Feature16)
12. 14T (turning for Feature14)
13. 18CDR (center drilling (for set-up) for Feature18)
14. 13EGV (external grooving for Feature13)

15. 15CHA (chamfering for Feature15)
16. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left
17. 8FM (milling for Feature8)

Setup4:
Machine: CNC Turning Center
Tool Approach: Right
18. 2RSU (rough surfacing for Feature2)
19. 2FSU (finish surfacing for Feature2)

Setup5:
Machine: Vertical miller
Tool Approach: Right
20. 9FM (milling for Feature9)

Setup6:
Machine: CNC Turning Center
Tool Approach: Left
21. 11RSU (rough surfacing for Feature11)
22. 11FSU (finish surfacing for Feature11)

Setup7:
Machine: External grinder
Tool Approach: Right
23. 3REG (rough grinding external cylinder for Feature3)

Setup8:
Machine: CNC Turning Center
Tool Approach: Left
24. 12RT (rough turning for Feature12)
25. 12FT (finish turning for Feature12)

Setup9:
Machine: External grinder
Tool Approach: Right
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup10:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration4: 10

Iteration 5:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)

2 . 10FSU (surfacing for Feature10)
3 . 5T (turning for Feature5)
4 . 17CDR (center drilling (for set-up) for Feature17)
5 . 7T (turning for Feature7)
6 . 6CHA (chamfering for Feature6)
7 . 4EGV (external grooving for Feature4)
8 . 3RT (rough turning for Feature3)
9 . 3FT (finish turning for Feature3)
10. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
11. 14T (turning for Feature14)
12. 16FSU (surfacing for Feature16)
13. 18CDR (center drilling (for set-up) for Feature18)
14. 13EGV (external grooving for Feature13)
15. 15CHA (chamfering for Feature15)
16. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: CNC Turning Center
Tool Approach: Right
17. 2RSU (rough surfacing for Feature2)
18. 2FSU (finish surfacing for Feature2)

Setup4:
Machine: Vertical miller
Tool Approach: Left
19. 8FM (milling for Feature8)

Setup5:
Machine: CNC Turning Center
Tool Approach: Left
20. 11RSU (rough surfacing for Feature11)
21. 11FSU (finish surfacing for Feature11)

Setup6:
Machine: Vertical miller
Tool Approach: Right
22. 9FM (milling for Feature9)

Setup7:
Machine: CNC Turning Center
Tool Approach: Left
23. 12RT (rough turning for Feature12)
24. 12FT (finish turning for Feature12)

Setup8:
Machine: External grinder
Tool Approach: Right
25. 3REG (rough grinding external cylinder for Feature3)
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup9:
Machine: External grinder

Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration5: 9

Iteration 6:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 5T (turning for Feature5)
3 . 10FSU (surfacing for Feature10)
4 . 17CDR (center drilling (for set-up) for Feature17)
5 . 7T (turning for Feature7)
6 . 6CHA (chamfering for Feature6)
7 . 3RT (rough turning for Feature3)
8 . 3FT (finish turning for Feature3)
9 . 4EGV (external grooving for Feature4)
10. 5ETT (turning external thread screw for Feature5)
11. 2RSU (rough surfacing for Feature2)
12. 2FSU (finish surfacing for Feature2)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 14T (turning for Feature14)
14. 16FSU (surfacing for Feature16)
15. 18CDR (center drilling (for set-up) for Feature18)
16. 13EGV (external grooving for Feature13)
17. 15CHA (chamfering for Feature15)
18. 14ETT (turning external thread screw for Feature14)
19. 11RSU (rough surfacing for Feature11)
20. 11FSU (finish surfacing for Feature11)

Setup3:
Machine: Vertical miller
Tool Approach: Left
21. 8FM (milling for Feature8)

Setup4:
Machine: CNC Turning Center
Tool Approach: Left
22. 12RT (rough turning for Feature12)
23. 12FT (finish turning for Feature12)

Setup5:
Machine: Vertical miller
Tool Approach: Right
24. 9FM (milling for Feature9)

Setup6:
Machine: External grinder
Tool Approach: Right
25. 3REG (rough grinding external cylinder for Feature3)

26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup7:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration6: 7

Iteration 7:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 5T (turning for Feature5)
3 . 10FSU (surfacing for Feature10)
4 . 17CDR (center drilling (for set-up) for Feature17)
5 . 7T (turning for Feature7)
6 . 3RT (rough turning for Feature3)
7 . 3FT (finish turning for Feature3)
8 . 6CHA (chamfering for Feature6)
9 . 4EGV (external grooving for Feature4)
10. 2RSU (rough surfacing for Feature2)
11. 2FSU (finish surfacing for Feature2)
12. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 14T (turning for Feature14)
14. 16FSU (surfacing for Feature16)
15. 18CDR (center drilling (for set-up) for Feature18)
16. 13EGV (external grooving for Feature13)
17. 15CHA (chamfering for Feature15)
18. 11RSU (rough surfacing for Feature11)
19. 11FSU (finish surfacing for Feature11)
20. 14ETT (turning external thread screw for Feature14)
21. 12RT (rough turning for Feature12)
22. 12FT (finish turning for Feature12)

Setup3:
Machine: Vertical miller
Tool Approach: Left
23. 8FM (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right
24. 9FM (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right

25. 3REG (rough grinding external cylinder for Feature3)
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration7: 6

<u>Iteration 8:</u>

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 5T (turning for Feature5)
3 . 10FSU (surfacing for Feature10)
4 . 17CDR (center drilling (for set-up) for Feature17)
5 . 3RT (rough turning for Feature3)
6 . 3FT (finish turning for Feature3)
7 . 7T (turning for Feature7)
8 . 6CHA (chamfering for Feature6)
9 . 2RSU (rough surfacing for Feature2)
10. 2FSU (finish surfacing for Feature2)
11. 4EGV (external grooving for Feature4)
12. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 14T (turning for Feature14)
14. 16FSU (surfacing for Feature16)
15. 18CDR (center drilling (for set-up) for Feature18)
16. 13EGV (external grooving for Feature13)
17. 11RSU (rough surfacing for Feature11)
18. 11FSU (finish surfacing for Feature11)
19. 15CHA (chamfering for Feature15)
20. 12RT (rough turning for Feature12)
21. 12FT (finish turning for Feature12)
22. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left
23. 8FM (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right
24. 9FM (milling for Feature9)

Setup5:
Machine: External grinder

Tool Approach: Right
25. 3REG (rough grinding external cylinder for Feature3)
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration8: 6

Iteration 9:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 5T (turning for Feature5)
3 . 10FSU (surfacing for Feature10)
4 . 3RT (rough turning for Feature3)
5 . 3FT (finish turning for Feature3)
6 . 17CDR (center drilling (for set-up) for Feature17)
7 . 7T (turning for Feature7)
8 . 2RSU (rough surfacing for Feature2)
9 . 2FSU (finish surfacing for Feature2)
10. 6CHA (chamfering for Feature6)
11. 4EGV (external grooving for Feature4)
12. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 14T (turning for Feature14)
14. 16FSU (surfacing for Feature16)
15. 18CDR (center drilling (for set-up) for Feature18)
16. 11RSU (rough surfacing for Feature11)
17. 11FSU (finish surfacing for Feature11)
18. 13EGV (external grooving for Feature13)
19. 12RT (rough turning for Feature12)
20. 12FT (finish turning for Feature12)
21. 15CHA (chamfering for Feature15)
22. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left
23. 8FM (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right
24. 9FM (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right

25. 3REG (rough grinding external cylinder for Feature3)
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left

28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration9: 6

Iteration 10:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right

1 . 1T (turning for Feature1)
2 . 5T (turning for Feature5)
3 . 3RT (rough turning for Feature3)
4 . 3FT (finish turning for Feature3)
5 . 10FSU (surfacing for Feature10)
6 . 17CDR (center drilling (for set-up) for Feature17)
7 . 2RSU (rough surfacing for Feature2)
8 . 2FSU (finish surfacing for Feature2)
9 . 7T (turning for Feature7)
10. 6CHA (chamfering for Feature6)
11. 4EGV (external grooving for Feature4)
12. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left

13. 14T (turning for Feature14)
14. 16FSU (surfacing for Feature16)
15. 11RSU (rough surfacing for Feature11)
16. 11FSU (finish surfacing for Feature11)
17. 18CDR (center drilling (for set-up) for Feature18)
18. 12RT (rough turning for Feature12)
19. 12FT (finish turning for Feature12)
20. 13EGV (external grooving for Feature13)
21. 15CHA (chamfering for Feature15)
22. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left

23. 8FM (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right

24. 9FM   (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right
25. 3REG   (rough grinding external cylinder for Feature3)
26. 3FEG   (finish grinding external cylinder for Feature3)
27. 2ENG   (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG   (grinding end surface for Feature11)
29. 12REG   (rough grinding external cylinder for Feature12)
30. 12FEG   (finish grinding external cylinder for Feature12)

Number of setups for Iteration10: 6

Iteration 11:

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T   (turning for Feature1)
2 . 3RT   (rough turning for Feature3)
3 . 3FT   (finish turning for Feature3)
4 . 5T   (turning for Feature5)
5 . 10FSU   (surfacing for Feature10)
6 . 2RSU   (rough surfacing for Feature2)
7 . 2FSU   (finish surfacing for Feature2)
8 . 17CDR   (center drilling (for set-up) for Feature17)
9 . 7T   (turning for Feature7)
10. 6CHA   (chamfering for Feature6)
11. 4EGV   (external grooving for Feature4)
12. 5ETT   (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 14T   (turning for Feature14)
14. 11RSU   (rough surfacing for Feature11)
15. 11FSU   (finish surfacing for Feature11)
16. 16FSU   (surfacing for Feature16)
17. 12RT   (rough turning for Feature12)
18. 12FT   (finish turning for Feature12)
19. 18CDR   (center drilling (for set-up) for Feature18)
20. 13EGV   (external grooving for Feature13)
21. 15CHA   (chamfering for Feature15)
22. 14ETT   (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left
23. 8FM   (milling for Feature8)

Setup4:

Machine: Vertical miller
Tool Approach: Right
24. 9FM (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right
25. 3REG (rough grinding external cylinder for Feature3)
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration11: 6

<u>Iteration 12:</u>

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 3RT (rough turning for Feature3)
3 . 3FT (finish turning for Feature3)
4 . 5T (turning for Feature5)
5 . 2RSU (rough surfacing for Feature2)
6 . 2FSU (finish surfacing for Feature2)
7 . 10FSU (surfacing for Feature10)
8 . 17CDR (center drilling (for set-up) for Feature17)
9 . 7T (turning for Feature7)
10. 6CHA (chamfering for Feature6)
11. 4EGV (external grooving for Feature4)
12. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 11RSU (rough surfacing for Feature11)
14. 11FSU (finish surfacing for Feature11)
15. 14T (turning for Feature14)
16. 12RT (rough turning for Feature12)
17. 12FT (finish turning for Feature12)
18. 16FSU (surfacing for Feature16)
19. 18CDR (center drilling (for set-up) for Feature18)
20. 13EGV (external grooving for Feature13)
21. 15CHA (chamfering for Feature15)
22. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left
23. 8FM (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right
24. 9FM (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right
25. 3REG (rough grinding external cylinder for Feature3)
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration12: 6

<u>Iteration 13:</u>

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 3RT (rough turning for Feature3)
3 . 3FT (finish turning for Feature3)
4 . 2RSU (rough surfacing for Feature2)
5 . 2FSU (finish surfacing for Feature2)
6 . 5T (turning for Feature5)
7 . 10FSU (surfacing for Feature10)
8 . 17CDR (center drilling (for set-up) for Feature17)
9 . 7T (turning for Feature7)
10. 6CHA (chamfering for Feature6)
11. 4EGV (external grooving for Feature4)
12. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 12RT (rough turning for Feature12)
14. 11RSU (rough surfacing for Feature11)
15. 11FSU (finish surfacing for Feature11)
16. 12FT (finish turning for Feature12)
17. 14T (turning for Feature14)
18. 16FSU (surfacing for Feature16)
19. 18CDR (center drilling (for set-up) for Feature18)
20. 13EGV (external grooving for Feature13)
21. 15CHA (chamfering for Feature15)
22. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller
Tool Approach: Left

23. 8FM (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right
24. 9FM (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right
25. 3REG (rough grinding external cylinder for Feature3)
26. 3FEG (finish grinding external cylinder for Feature3)
27. 2ENG (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG (grinding end surface for Feature11)
29. 12REG (rough grinding external cylinder for Feature12)
30. 12FEG (finish grinding external cylinder for Feature12)

Number of setups for Iteration13: 6

<u>Iteration 14:</u>

Setup1:
Machine: CNC Turning Center
Tool Approach: Right
1 . 1T (turning for Feature1)
2 . 3RT (rough turning for Feature3)
3 . 2RSU (rough surfacing for Feature2)
4 . 2FSU (finish surfacing for Feature2)
5 . 3FT (finish turning for Feature3)
6 . 5T (turning for Feature5)
7 . 10FSU (surfacing for Feature10)
8 . 17CDR (center drilling (for set-up) for Feature17)
9 . 7T (turning for Feature7)
10. 6CHA (chamfering for Feature6)
11. 4EGV (external grooving for Feature4)
12. 5ETT (turning external thread screw for Feature5)

Setup2:
Machine: CNC Turning Center
Tool Approach: Left
13. 12RT (rough turning for Feature12)
14. 11RSU (rough surfacing for Feature11)
15. 11FSU (finish surfacing for Feature11)
16. 12FT (finish turning for Feature12)
17. 14T (turning for Feature14)
18. 16FSU (surfacing for Feature16)
19. 18CDR (center drilling (for set-up) for Feature18)
20. 13EGV (external grooving for Feature13)
21. 15CHA (chamfering for Feature15)
22. 14ETT (turning external thread screw for Feature14)

Setup3:
Machine: Vertical miller

```
Tool Approach: Left
23. 8FM      (milling for Feature8)

Setup4:
Machine: Vertical miller
Tool Approach: Right
24. 9FM      (milling for Feature9)

Setup5:
Machine: External grinder
Tool Approach: Right
25. 3REG     (rough grinding external cylinder for Feature3)
26. 3FEG     (finish grinding external cylinder for Feature3)
27. 2ENG     (grinding end surface for Feature2)

Setup6:
Machine: External grinder
Tool Approach: Left
28. 11ENG    (grinding end surface for Feature11)
29. 12REG    (rough grinding external cylinder for Feature12)
30. 12FEG    (finish grinding external cylinder for Feature12)

Number of setups for Iteration14: 6
```

Appendix C: CNC Codes Generated for Producing the Shaft

The CNC codes generated by Master CAM for the shaft based on the final process plan produced by the IPPS_R system are presented. Standard codes for NC programming are given in Appendix D.

```
%
O0000
G21
(PROGRAM NAME - SHAFT DATE=DD-MM-YY - 15-12-03 TIME=HH:MM - 09:51)
(TOOL - 1 OFFSET - 1)
(LROUGH OD ROUGH RIGHT - 80 DEG.  INSERT - CNMG 12 04 08)
G0T0101
G97S3600M13
G0G54X24.4Z4.7
G50S3600
G96S295
G99G1Z2.F.2
Z-64.8
X28.
X30.828Z-63.386
G0Z4.7
X21.4
G1Z-60.175
X24.4
X27.228Z-58.761
G0Z4.7
X18.4
G1Z2.
Z-60.175
X21.8
X24.628Z-58.761
G28U0.W0.M05
T0100
M01
(TOOL - 2 OFFSET - 2)
(LGROOVE OD GROOVE CENTER - NARROW INSERT - N151.2-185-20-5G)
G0T0202
G97S1289M13
G0G54X28.4Z-61.3
G50S3600
G96S115
G1X17.4F.1
G0X28.4
Z-61.05
G1X17.4
X17.5Z-61.1
G0X28.4
Z-62.914
X27.228
G1X24.4Z-61.5
X17.
X17.5Z-61.25
G0X26.828
```

```
Z-59.436
G1X24.Z-60.85
X17.
X17.5Z-61.1
G0X27.228
Z-62.914
X26.828
G1X24.Z-61.5
X17.
X17.5Z-61.25
G0X26.828
Z-59.436
G1X24.Z-60.85
X17.
X17.5Z-61.1
G0X26.828
G28U0.W0.M05
T0200
M01
(TOOL - 3 OFFSET - 3)
(LFINISH OD FINISH RIGHT - 35 DEG.  INSERT - VNMG 16 04 08)
G0T0303
G97S3600M13
G0G54X18.Z5.05
G50S3600
G96S295
G1Z3.05F.3
Z-61.
X20.828Z-59.586
G0Z4.7
X16.4
G1Z2.
Z-22.8
X19.228Z-21.386
G28U0.W0.M05
T0300
M01
(TOOL - 4 OFFSET - 4)
(LFACE ROUGH FACE RIGHT - 80 DEG.  INSERT - CNMG 12 04 08)
G0T0404
G97S3600M13
G0G54X16.534Z0.
G50S3600
G96S295
G1X-6.971F.2
G0Z2.
G28U0.W0.M05
T0400
M01
(TOOL - 5 OFFSET - 5)
(LDRILL DRILL 3. DIA.  INSERT - 3. DRILL)
G0T0505
G97S0M15
G0G54X0.Z5.
Z2.
G98G1Z-.901F2.
G0Z5.
```

```
G28U0.W0.M05
T0500
M01
(TOOL - 1 OFFSET - 1)
(LROUGH OD ROUGH RIGHT - 80 DEG.  INSERT - CNMG 12 04 08)
G0T0101
G97S3600M13
G0G54X13.9Z2.5
G50S3600
G96S295
G99G1Z-9.F.2
X16.4
G0Z2.5
X13.5
G1Z-9.51
X16.4Z-11.25
G0X19.
G28U0.W0.M05
T0100
M01
(TOOL - 2 OFFSET - 2)
(LGROOVE OD GROOVE CENTER - NARROW  INSERT - N151.2-185-20-5G)
G0T0202
G97S1664M13
G0G54X22.Z-23.5
G50S3600
G96S115
G1X13.F.1
G0X22.
Z-23.35
G1X13.
X13.06Z-23.38
G0X22.
Z-24.914
X20.828
G1X18.Z-23.5
X13.
G0X20.828
Z-21.936
G1X18.Z-23.35
X13.
G0X20.828
G28U0.W0.M05
T0200
M01
(TOOL - 6 OFFSET - 6)
(LTHREAD OD THREAD RIGHT  INSERT - R166.0G-16UN01-100)
G0T0606
G97S1345M13
G0G54X20.Z-4.887
X15.485
G32Z-21.5E1.75
G0X20.
Z-4.979
X15.153
G32Z-21.5E1.75
G0X20.
```

```
Z-5.052
X14.889
G32Z-21.5E1.75
G0X20.
Z-5.115
X14.661
G32Z-21.5E1.75
G0X20.
Z-5.171
X14.459
G32Z-21.5E1.75
G0X20.
Z-5.222
X14.275
G32Z-21.5E1.75
G0X20.
Z-5.269
X14.106
G32Z-21.5E1.75
G0X20.
Z-5.269
X14.106
G32Z-21.5E1.75
G0X20.
Z-4.887
(Flip Stock)
G28U0.W0.M05
T0600
M01
(TOOL - 1 OFFSET - 1)
(LROUGH OD ROUGH RIGHT - 80 DEG.  INSERT - CNMG 12 04 08)
G0T0101
G97S3600M13
G0G54X24.667Z2.5
G50S3600
G96S295
G1Z-37.858F.2
G0Z2.5
X21.333
G1Z-.8
G0Z2.5
X18.
G1Z-38.
X24.4
G28U0.W0.M05
T0100
M01
(TOOL - 3 OFFSET - 3)
(LFINISH OD FINISH RIGHT - 35 DEG.  INSERT - VNMG 16 04 08)
G0T0303
G97S3600M13
G0G54X20.6Z-14.
G50S3600
G96S295
X18.
G1Z-16.F.3
Z-38.
```

```
X20.828Z-36.586
G0Z2.5
X16.
G1Z-15.5
X18.
X20.828Z-14.086
G28U0.W0.M05
T0300
M01
(TOOL - 4 OFFSET - 4)
(LFACE ROUGH FACE RIGHT - 80 DEG.  INSERT - CNMG 12 04 08)
G0T0404
G97S3600M13
G0G54X11.629Z0.
G50S3600
G96S295
G1X-6.971F.2
G0Z2.
G28U0.W0.M05
T0400
M01
(TOOL - 5 OFFSET - 5)
(LDRILL DRILL 3. DIA.  INSERT - 3. DRILL)
G0T0505
G97S0M15
G0G54X0.Z5.
Z2.
G98G1Z-.901F2.
G0Z5.
G28U0.W0.M05
T0500
M01
(TOOL - 2 OFFSET - 2)
(LGROOVE OD GROOVE CENTER - NARROW  INSERT - N151.2-185-20-5G)
G0T0202
G97S1664M13
G0G54X22.Z-16.
G50S3600
G96S115
G99G1X13.F.1
G0X22.
Z-15.85
G1X13.
X13.06Z-15.88
G0X22.
Z-17.414
X20.828
G1X18.Z-16.
X13.
G0X20.828
Z-14.436
G1X18.Z-15.85
X13.
G0X20.828
G28U0.W0.M05
T0200
M01
```

```
(TOOL - 3 OFFSET - 3)
(LROUGH OD FINISH RIGHT - 35 DEG.  INSERT - VNMG 16 04 08)
G0T0303
G97S3600M13
G0G54X12.531Z2.5
G50S3600
G96S295
G1Z-.234F.3
X16.Z-1.969
X18.828Z-.554
G28U0.W0.M05
T0300
M01
(TOOL - 6 OFFSET - 6)
(LTHREAD OD THREAD RIGHT  INSERT - R166.0G-16UN01-100)
G0T0606
G97S1345M13
G0G54X20.Z4.113
X15.485
G32Z-14.E1.75
G0X20.
Z4.021
X15.153
G32Z-14.E1.75
G0X20.
Z3.948
X14.889
G32Z-14.E1.75
G0X20.
Z3.885
X14.661
G32Z-14.E1.75
G0X20.
Z3.829
X14.459
G32Z-14.E1.75
G0X20.
Z3.778
X14.275
G32Z-14.E1.75
G0X20.
Z3.731
X14.106
G32Z-14.E1.75
G0X20.
Z3.731
X14.106
G32Z-14.E1.75
G0X20.
Z4.113
G28U0.W0.M05
T0600
M30
%
```

Appendix D: Standard Codes for NC Programming

Appendix D.1: Address Words Used in NC Programming

Address	**Meaning**
A	Rotation about the x-axis
B	Rotation about the y-axis
C	Rotation about the z-axis
F	Feed rate commend
G	Preparatory function
I	Circular interpolation: x-axis offset
J	Circular interpolation: y-axis offset
K	Circular interpolation: z-axis offset
M	Miscellaneous commands
N	Sequence number
R	Radius of arc or circle
S	Spindle speed
T	Tool number
U	Supplemental coordinate parallel to x-axis
V	Supplemental coordinate parallel to y-axis
W	Supplemental coordinate parallel to z-axis
X	x-axis data
Y	y-axis data
Z	z-axis data

Source: Singh, N. (1996), *Systems Approach to Computer-Integrated Design and Manufacturing,* pp. 252 – 255, Wiley, New York, USA.

Appendix D.2: G Code

G Code	Function
G00	Point-to-point positioning, high rate
G01	Linear interpolation, controlled feed rate
G02	Circular interpolation, clockwise
G03	Circular interpolation, counterclockwise
G04	Dwell, Exact stop
G05	High speed cycle machining
G06	Parabolic interpolation
G07	Controlled acceleration of feed rate to programmed value
G08	Controlled deceleration of feed rate to programmed value
G09	Exact stop
G10	Data setting
G11	Data setting mode cancel
G12	Three-dimensional interpolation
G15	Polar coordinates command cancel
G16	Polar coordinates command
G17	x-y Plane Selection
G18	z-x Plane Selection
G19	y-z Plane Selection
G20	Input in inch
G21	Input in mm
G22	Stored stroke check function on
G23	Stored stroke check function off
G27	Reference position return chuck
G28	Return the reference position
G29	Return from reference position
G30	2nd, 3rd and 4th reference position return
G31	Skip function
G33	Thread cutting, constant lead
G34	Thread cutting, increasing lead
G35	Thread cutting, decreasing lead
G37	Automatic tool length measurement
G39	Corner offset circular interpolation
G40	Cutter compensation cancel
G41	Cutter compensation left
G42	Cutter compensation right

G43	Tool length compensation, positive
G44	Tool length compensation, negative
G45	Tool offset increase
G46	Tool offset decrease
G47	Tool offset double increase
G48	Tool offset double decrease
G49	Tool length compensation cancel
G50	Scaling cancel
G51	Scaling
G52	Local coordinate system setting
G53	Machine coordinate system selection
G54	Linear shift, x
G55	Linear shift, y
G56	Linear shift, z
G57	Linear shift, xy
G58	Linear shift, xy
G59	Linear shift, yz
G60	Single direction positioning
G61	Exact stop mode
G62	Automatic corner override
G63	Tapping mode
G64	Cutting mode
G65	Macro call
G66	Macro modal call
G67	Macro modal call cancel
G68	Coordinate rotation
G69	Coordinate rotation cancel
G73	Peck drilling cycle
G74	Counter tapping cycle
G75	Plunge grinding cycle (0-GSC)
G76	Fine boring cycle
G77	Direct constant-dimension plunge grinding cycle (0-GSC)
G78	Continuous-feed surface grinding cycle (0-GSC)
G79	Intermittent-feed surface grinding cycle (0-GSC)
G80	Canned cycle cancel/external operation cancel
G81	Drilling cycle, spot boring cycle or external operation function
G82	Drilling cycle or counter boring cycle

G83	Peck drilling cycle
G84	Tapping cycle
G85	Boring cycle
G86	Boring cycle
G87	Back boring cycle
G88	Boring cycle
G89	Boring cycle
G90	Absolute command
G91	Increment command
G92	Setting for work coordinate system or clamp at maximum spindle speed
G94	Feed per minute
G95	Feed per rotation
G96	Constant cutting speed
G97	Spindle speed in revolutions per minute
G98	Return to initial point in canned cycle
G99	Return to R point in canned cycle

Source: Singh, N. (1996), *Systems Approach to Computer-Integrated Design and Manufacturing,* pp. 252 – 255, Wiley, New York, USA.

Appendix D.3: M Code

M Code	Function
M00	Program stop
M01	Optional stop
M02	End of program
M03	Spindle rotation in clock wise
M04	Spindle rotation in counterclockwise
M05	Spindle off (stop)
M06	Tool change
M08	Coolant on
M09	Coolant off
M10	Clamp on
M11	Clamp off
M13	Spindle on clock wise and coolant on
M14	Spindle on counterclockwise and coolant on
M15	Rapid slide motion in positive direction
M16	Rapid slide motion in negative direction
M19	Stop spindle in oriented position
M30	End of program

Source: Singh, N. (1996), *Systems Approach to Computer-Integrated Design and Manufacturing,* pp. 252 – 255, Wiley, New York, USA.

Appendix E: CNC Codes Generated for the Valve Cover

The CNC codes generated in the Master CAM environment for the valve cover based on the final process plan developed by the IPPS_R system are presented.

```
%
O0000(Valve Cover)
G21
( TOOL - 1 OFFSET - 1 )
( LFACE OD FINISH RIGHT - 35 DEG. INSERT - VNMG 16 04 08 )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0101
G18
G97S384M13
G0X132.578Z0.
G50S3600
G96S160
G99G1X-1.6F.4
G0Z2.
G30U0.V0.W0.M5
T0100
M01
( TOOL - 2 OFFSET - 2 )
( LFINISH ROUGH FACE RIGHT - 80 DEG. INSERT - CNMG 12 04 08 )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0202
G18
G97S463M13
G0X110.Z-26.022
G50S3600
G96S160
G1Z-28.022
Z-91.958
G2X111.029Z-92.R3.2
G1X125.
X127.828Z-90.586
G30U0.V0.W0.M5
T0200
M01
( TOOL - 8 OFFSET - 8 )
( LROUGH OD ROUGH RIGHT - 80 DEG. INSERT - CNMG 12 04 08 )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0808
G18
G97S507M13
G0X100.4Z2.5
G50S3600
G96S160
G1X100.403Z-14.823F.2
X103.231Z-13.409F.4
G30U0.V0.W0.M5
```

```
T0800
M01
( TOOL - 3 OFFSET - 3 )
( LGROOVE OD GROOVE RIGHT - NARROW INSERT - N151.2-185-20-5G )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0303
G18
G97S294M13
G0X104.Z-17.85
G50S3600
G96S96
G1X95.3F.04
G0X104.
Z-16.
G1X95.3
X96.04Z-16.37
G0X104.
Z-16.586
X102.828
G1X100.Z-18.
X95.
Z-17.255
G0X102.828
Z-17.264
G1X100.Z-15.85
X95.
Z-16.595
G0X102.828
X102.907
G30U0.V0.W0.M5
T0300
M01
( TOOL - 4 OFFSET - 4 )
( LDRILL DRILL 40. DIA. INSERT - 40. DRILL )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0404
G18
G97S190M13
G0X0.Z2.
G98G1Z-140.F91.7
G0Z2.
G30U0.V0.W0.M5
T0400
M01
( TOOL - 5 OFFSET - 5 )
( LROUGH ID ROUGH MIN. 25. DIA. - 80 DEG. INSERT - CCMT 12 04 04 )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0505
G18
G97S668M13
G0X76.2Z2.5
G50S3600
G96S160
G99G1Z-104.344F.3
```

```
G3X72.8Z-104.8R3.4
G1X29.972Z-103.386
G0Z2.5
X79.6
G1Z-101.4
G3X72.8Z-104.8R3.4
G1X69.972Z-103.386
G0Z1.25
X250.
G30U0.V0.W0.M5
T0500
M01
( TOOL - 6 OFFSET - 6 )
( LFINISH ID FINISH MIN. 25. DIA. - 55 DEG. INSERT - DCMT 11 T3 08 )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0606
G18
G97S637M13
G0X80.Z2.
G50S3600
G96S160
G1Z0.
Z-101.8
G3X73.6Z-105.R3.2
G1X70.772Z-103.586
G0Z-103.
X72.
G1Z-105.
X67.506
X64.678Z-103.586
G0Z1.25
X250.
G30U0.V0.W0.M5
T0600
M01
( TOOL - 7 OFFSET - 7 )
( LTHREAD OD THREAD RIGHT INSERT - R166.0G-16UN01-100 )
G30U0.V0.W0.
G50X250.Y0.Z250.
G0T0707
G18
G97S1345M13
G0X104.Z6.472
Z6.466
X99.237
G32Z-14.E2.
G0X104.
Z6.348
X98.829
G32Z-14.E2.
G0X104.
Z6.257
X98.513
G32Z-14.E2.
G0X104.
Z6.179
```

```
X98.245
G32Z-14.E2.
G0X104.
Z6.111
X98.008
G32Z-14.E2.
G0X104.
Z6.049
X97.794
G32Z-14.E2.
G0X104.
Z5.992
X97.596
G32Z-14.E2.
G0X104.
Z5.978
X97.546
G32Z-14.E2.
G0X104.
Z5.978
X97.546
G32Z-14.E2.
G0X104.
Z6.466
G30U0.V0.W0.M5
T0700
M30
%
```

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