

***OPTIMAL CHOICE OF A MACHINE TOOL
FOR A MACHINING JOB
IN CAE ENVIRONMENT***

A Thesis submitted for the degree of Doctor of Philosophy



By

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Abstract

Developments in cutting tools, coolants, drives, controls, tool changers, pallet changers and the philosophy of machine tool design have made ground breaking changes in machine tools and machining processes. Modern Machining Centres have been developed to perform several operations on several faces of a workpiece in a single setup. On the other hand industry requires high value added components, which have many quality critical features to be manufactured in an outsourcing environment as opposed to the traditional in-house manufacture. The success of this manufacture critically depends on matching the advanced features of the machine tools to the complexity of the component. This project has developed a methodology to represent the features of a machine tool in the form of an alphanumeric string and the features of the component in another string. The strings are then matched to choose the most suitable and economical Machine Tool for the component's manufacture.

Literature identified that block structure is the way to answer the question 'how to systematically describe the layout of such a machining centre'. Incomplete attempts to describe a block structure as alphanumeric strings were also presented in the literature. Survey on sales literature from several machine tool suppliers was investigated to systematically identify the features need by the user for the choice of a machine tool. Combining these, a new alphanumeric string was developed to represent machine tools. Using these strings as one of the 'key's for sorting a database of machine tools was developed. A supporting database of machine tools was also developed.

Survey on machining on the other hand identified, that machining features can be used as a basis for planning the machining of a component. It analysed various features and feature sets proposed and provided and their recognition in CAD models. Though a vast number of features were described only two sets were complete sets. The project was started with one of them, (the other was carrying too many unwanted details for the task of this project) machining features supported by 'Expert Machinist' software. But when it became unavailable a 'Feature set' along those lines were defined and used in the generation of an alphanumeric string to represent the work. Comparing the two strings led the choice of suitable machines from the database.

The methodology is implemented as a bolt on software incorporated within Pro/Engineer software where one can model any given component using cut features (mimicking machining operation) and produce a list of machine tools having features for the machining of that component. This will enable outsourcing companies to identify those Precision Engineers who have the machine tools with the matching capabilities. Supporting software and databases were developed using Access Database, Visual Basic and C with Pro/TOOLKIT functions. The resulting software suite was tested on several case studies and found to be effective.

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Chapter 1: Introduction

Foresight [1] advocates that '*Migration to Higher Value Added Service*' and '*Restructuring of Manufacturing Enterprises into Makers, Innovators and Integrators*' are some of the internal responses of the manufacturing industry for the global manufacturing trends. Outsourcing is at the heart of these responses. In simple terms outsourcing can be defined as the transfer of services or functions previously performed within the organization to a provider outside the organization. A lot of research work is being carried out on this new phenomenon, outsourcing. However, Berggen, C. & Bengtsson, L. [2] identify that in Manufacturing Outsourcing the research work is concentrated on management level (Buyer-supplier relationship) and work is still to be done in linking Design and Manufacturing to the outsourcing framework.

Provision of metal cutting operations often called 'Precision Engineering' services, is a key manufacturing activity in the UK. In the past all Original Equipment Manufacturer (OEM) had the so-called precision engineering activity in-house, but many OEM's now outsource this activity to precision engineers.

Developments in cutting tools, coolants, drives, controls, tool changers, pallet changers and the philosophy of machine tool design have made ground breaking changes in machine tools and machining processes and the time taken for cutting is almost the same whether a sophisticated or simple machine tool is used. Sophisticated machines are needed only to machine complex parts. Thus the key task in outsourcing machining work is 'the matching of the work to the machine tool in which it can be manufactured'. This research is focussed on this and is aimed at developing a systematic methodology to choose a machine tool of matching features to the complexity of the machining job presented. In order to understand the implications and define the aim and objectives of the work investigations were carried out under three broad topics.

They are

1. Historical development of Machine Tools
2. Change in Industrial Practice
3. The nature of the Components

Following sections gives a brief description of these and establish the aim and objectives of the research.

1.1 Historical Overview of Machine Tools

Machine tool is a power driven appliance to bring the cutting tool and the work piece in contact and to have a relative motion executing the cut that transforms the raw stock into a finished or semi-finished component. Early Machine tools have specialized in a specific manufacturing process or a collection of few such processes.

With developments rectifying all technological shortcomings a major rethink on functionality took place. Similar to a shopping centre where one can find all types of goodies under one roof, a 'Machining Centre' capable of providing several functions which were traditionally performed by different groups of machines such as mills, drills, shapers and so on was developed [3,4]. With the development of such machining centres the ability to know the capabilities of a machine tool simply by looking at the name has become a thing of the past. While the process names such as turning, end milling etc are used to describe the processes, the structure and appearance of the machines that perform these operations can be completely different.

A major enhancement to Machine tools came from the development of controllers, which controlled the functions such as motion, spindle, feed-rate, failure diagnostic, coolant, chip, tool changers, pallet changers, memory storage etc. This has almost eliminated the need for skilled machinists and substantially reduced idle time in machine tools. Researchers from the Soviet Union like Vragov [5], Portman [6] and Voronov, [7] proposed various levels of coding system to describe the structure of a machine tool. But no published work has appeared from them after the fall of the Soviet Union. *Ito* and *Shinno* [8] provided the motion function as blocks to represent machine tools system. This attempt again has not given any substantial result.

In summary, many motion providing functions are incorporated and controlled in a single machine tool providing huge flexibility and the trend is to incorporate more functions. Limited work has been done on developing a generic way to describe a machine tool. Furthermore technological advancements created a trend that is 'addition of more features to the already

complex machine tool to produce more complex components'. **This has created the necessity for a systematic methodology to represent the current and future machine tools.**

1.2 Change in Industrial Practice

Roth [9] states that their transfer lines for the different automobile manufacturers were based on the objective parts family consisting of the 4C's, the Cylinder block, Cylinder head, Crankshaft and Camshaft. Thus the fundamental considerations in the early machining centres were (a) objective parts family and (b) generation of the required form generating functions. This is in contrast to the situation created by outsourcing where the outsourcer and the precision engineer do not know the other side. The 'Precision Engineering Companies' have a variety of machine tools ranging from traditional lathes and milling machines to CNC machining centres and they take contract work for these machines. They charge an hourly rate for the machine, operator and the overhead for costing the work before adding a profit. The hourly rate for the machine depends on the cost of the machine and thus the rate charged by different companies may vary widely depending on which machine they intend to use for production. **Therefore an easy method to match the capabilities of the machine tool to the complexities of the component to be machined is fundamental for outsourcers and precision engineers for economical and high quality manufacture.**

1.3 High Value-added Components

Within special industrial sectors such as the pharmaceutical, aeronautical and food engineering there are a group of components that are called high value added components. These components weigh few kilograms, machined out of standard stock and have special features. The cost of the raw stock of these components are often less than one hundred pounds, but the finished component costs several thousand pounds and the reason for the high cost is the high number of features present in the components. They are often manufactured as one-offs and the features are quality critical. They need to be manufactured using code generated by CAD/CAM software and proven by simulation.

1.4 Statement of the Problem

Complex machine tools with varying capabilities have been and are being developed but no generic method to describe the structure of the machine has been fully developed. Unlike in the past the precision engineer does not know the work in advance to buy a suitable machine tool and hence an easy way to choose a matching machine to a job is needed to facilitate outsourcing. High value added components demand an easy way of generating, proving and transferring NC codes from design to the machine tool. A methodology to describe the capability of a machine tool and an easy way to choose matching machine tools to a given job is the fundamental requirement and this thesis is aimed at addressing this requirement.

1.5 Aim and Objectives

Aim: The broad aim of this research is to develop a systematic methodology to choose a machine tool of matching features to the complexity of the machining job presented.

Objectives:

1. To classify Machine Tools based on considerations of axes, sizes, spindles, tool magazines, palettes, controllers etc. and the development of an alphanumeric code to represent a machine uniquely.
2. To develop a sample database of commercially available machine tools from which machine tools with common alphanumeric code can be retrieved.
3. To extract machining features and relevant information from a CAD model produced by Pro/Engineer using the API, Pro-toolkit
4. To choose required machining characteristics features to generate the alphanumeric code of the machine tools suitable for the given machining job.
5. To develop a software incorporating facilities to achieve the above objectives and the required interfaces for inputting and outputting.

1.6 Summary Findings

Literature survey on Machine tools identified three major points. They are

- i. Advancements of Machining Technology have reached a point where high quality tools have been developed, coolants are devised, control systems and controllers were developed, drive technologies were improved and better design methods were employed. Machining Centres capable of performing several processes traditionally carried out by different machines were developed. Analysis of some of the commercially available machine tools pointed that there are machine tools which have a widely varied motion functions and degrees of freedom and the trend towards the future is to have further increase in sophistication due to addition of more degrees of freedom.
- ii. Block structure of a Machine Tool divided it into two sections as the main flow of forces and sub flow or forces. This laid the foundation for the method of describing a Machine Tool by an Alphanumeric string.
- iii. Shino and Ito have presented a design methodology for a Machine Tool. This highlights that the primary step is to provide the motion functions in block structure, which is then enhanced by structural design methods for mechanical properties. This shows that future machines can have more blocks providing more complex motion functions. This has been useful in the development of the alphanumeric code.

These are described in Chapter 2. In a similar fashion survey on machining revealed that machining operations can be best described by Machining Features. Two 'Feature Sets', one provided by ISO through their standard ISO 10303 and the other provided by Expert Machinist, an additional software module in Pro/Engineer suite, have been discussed in Appendix I.

From these the critical surface characteristics to describe machining features were established. A new set of cut features, were developed from them.

Based on the findings from the literature a two branch methodology to match the work with the capabilities of the machine tool was established. The established methodology was implemented as bolt-on software with CAE package (Pro/Engineer) using its Application Programmer's Interface, Pro/Toolkit. A matching database of commercially available machine tools also was created. The developed software has been tested with several high value added components for validity.

1.7 Structure of the thesis

Chapter 2 provides analysis of traditional machine tools, and the technological developments that led to the development of machining centres. It further discuss about various research work that was carried out to represent machining tools using codes and structural layout.

Chapter 3 sees feature based machining as an efficient way for planning machining. It therefore provides a comprehensive survey on feature based machining. From the survey the important characteristics for machining planning were identified. Two sets of machining features were found to be complete. One of them was followed in the project and when that became unavailable in the market a new feature set was defined. This chapter describe them.

Chapter 4 describes the methodology to choose a machine tool of matching capability to those required by the complexity of the component.

Chapter 5 describes the implementation of the methodology using Access database, Pro Engineer for CAD, Pro/TOOLKIT for application program interface and Visual Basic to analysis and select the suitable choice of machine tool for the component using the alphanumeric codes.

Chapter 6 provide a detailed case study to show the process of creation of the workpiece as cuts (mimicking material removal) in CAD, identification of machining features using Pro/TOOLKIT generation of alphanumeric codes and selection of suitable machine tool for machining.

Chapter 7 discusses the results of the research work and draws conclusions.

The appendixes included in the project are

APPENDIX A – Brief history Machine Tool Survey

APPENDIX B – Possible combination of 3 and 5 axis machine tools

APPENDIX C – Arbitrary workpiece and its machining features

APPENDIX D – Pro/TOOLKIT programme code

APPENDIX E – Visual Basic programme code

APPENDIX F – Theory used in the Software

APPENDIX G – Catalogue of Dugard VMC 660

APPENDIX H – BS4656-30 Standards

Chapter 2 Literature Survey – Machine Tools

2.0 Introduction

For the purpose of classifying the machine tools according to its capabilities and usage complexities a study on the use perspective was needed and Table 2.1 shows the essence of a comprehensive survey on traditional machine tools from the use perspective. It describes the developments under the following five categories:

- Development in the Processes
- Mechanical Synchronisation
- Development of Cutting Tools and Coolants
- Early NC and Automation
- Development of Controls and Controllers

Machining Centres perform a multitude of tasks. A detailed survey of machining centres was carried out and the details can be categorised into the following for easy comprehension.

- Horizontal machining centres
- Vertical machining centres
- Five axis machining centres
- Turning Centres
- Turning Centre with Milling Heads

The details of the findings are summarised in Table 2.2.

Table 2.1: Historical Developments of Machine Tool

Development in Process	Mechanical Synchronisation	Development of Cutting tools and Coolant	NC and Automation	Development of Control and Controllers
<p>Need for Shape arose power assisted tools to develop into processes <i>Cylindrical Surface</i> EXTERNAL</p> <ul style="list-style-type: none"> - Carried out using lathe and the process was called Turning. - Turning underwent further development into Taper Turning and Screw Cutting. - Process held the workpiece in rotating chuck and moved the cutting tool along rotational axis. Factors influencing were <ol style="list-style-type: none"> a) Speed of turning the chuck b) Depth of the cut c) Direction and Feed of cutting tool <p>INTERNAL</p> <ul style="list-style-type: none"> - Carried out using Drills and the process was called Drilling - Drilling underwent further development into reaming, spot facing, countersinking, counter boring and tapping. - Process gripped and revolved the cutting tool holding the workpiece stationary. Factors influencing were <ol style="list-style-type: none"> a) Direction of cutting tool b) Rotational speed of cutting tool c) Holding of workpiece <p><i>Flat & Planar Surfaces</i></p> <ul style="list-style-type: none"> - Carried out using Shaper - Process held the workpiece and cutting tool move back and forth removing small rectangular block or material. Factors influencing were <ol style="list-style-type: none"> a) Depth of cut b) Back and forth motion of cutter c) The stroke length - Carried out using Planning Machine - Cutting tool is held and the workpiece is moved back and forth beneath it. Factors influencing were <ol style="list-style-type: none"> a) Cutter b) Speed of workpiece motion c) Depth of cut - Carried out using Milling Machine and the process were called as Milling. - Milling underwent further development with its tool and direction of the cutting tool to incorporate cylindrical and form surfaces - Process held a rotating cutting and its axis parallel to the cutting workpiece and factors influencing were <ol style="list-style-type: none"> a) Rotational Axis of cutter b) Direction of cutter c) Depth of cut 	<p>Need for repeated operation at constant interval was achieved using mechanical and Electro Mechanical mechanisms</p> <p><i>Constant Length</i></p> <ul style="list-style-type: none"> - Stopper and Trippers <p><i>Repetitive production and interchangeable cutting process</i></p> <ul style="list-style-type: none"> - Was achieved by Capstan and Turret Lathe using <ol style="list-style-type: none"> a) Pre set cutting tools b) Index-able and multi-station Cutting tool head - Reducing setting up time - Increasing rapid succession of tool change <p><i>Memory & Control</i></p> <ul style="list-style-type: none"> - Introduction of Electro-Mechanical Mechanisms - Further Development in Capstan and Turret Lathe with power feed and saddles - Reduced intervention of skilled workers <p><i>Tool Holders</i></p> <p>Single tool holder</p> <ul style="list-style-type: none"> - Single end cutting tool - Double end cutting tools <p>Multiple tool holder</p> <ul style="list-style-type: none"> - Turret head <p><i>Tool Storage</i></p> <ul style="list-style-type: none"> - Mobile cart - Turret - Magazine <ol style="list-style-type: none"> a) Matrix b) Chain c) Drum d) Umbrella <p><i>Tool Changers</i></p> <ul style="list-style-type: none"> - Turret - Single Arm - Twin Arm 	<p>Tool developed machines and machines developed tools. High Strength and High Speed paved way for increased demand for Cutting tool.</p> <p><i>Cutting tools</i></p> <p>Demand for higher strength and rapid manufacturing saw development of</p> <ul style="list-style-type: none"> - High Carbon Steel - High Speed Steel <p>Longer Machining Time, Higher cutting force & speeds, Deeper cuts developed cutting tool of</p> <ul style="list-style-type: none"> - Inserts - Coated tool tips - Aided by coolants <p><i>Coolants</i></p> <p>Initial use were to remove excessive heat Development brought in the coolants to</p> <ul style="list-style-type: none"> - Lubricate - Minimize built up edges - Protect tool and workpiece from corrosion - Improve finish - Flush Chips <p>Types</p> <ol style="list-style-type: none"> a) Straight oil b) Water soluble <p><i>Coolant Application</i></p> <ul style="list-style-type: none"> - Manual - Flood - Mist - Chilled - High Pressure 	<p>To avoid physical labour and mundane repetitive single or multiple operations.</p> <p><i>Numerical Control Automation</i></p> <ul style="list-style-type: none"> - Frank Stulen at Parsons Corporation in collaboration with MIT developed numerical control - Programmed operation used pre-recorded information stored in numerical format - Initiated use of electronic controls - Numerical Data was Stored in formats of <ol style="list-style-type: none"> a) Punch tapes b) Cards c) Magnetic tapes 	<p>Controllers converted the part programme instruction into signals to control various actions of machine tool.</p> <p><i>Function of a Controller</i></p> <ul style="list-style-type: none"> - Pre preparation considering machine tool and cutting tools for the workpiece - Production of memory device for automation - Controller then decodes the memory device - Decoded data are converted to electromechanical signals for the switches to control - Tolerant to Cutting tool failures and Collisions <p><i>Advancement brought in</i></p> <ul style="list-style-type: none"> - Handling multiple axes - Automated tool and pallet changes - Feedback system - Tool failure detection - Coolant system - Reduction of production time & cost - Elimination of skilled works

Table 2.2: Machining Centres

Machining Centres: is a single station computer numerically controlled machine tool capable of milling, drilling, boring, reaming and tapping

Horizontal Machining Centre	Vertical Machining Centre	Five Axis Machining Centre	Turning Centre	Turning Centre with Milling Heads
<p>Working Principle : Spindle is horizontal to the work table and whose motion is back and forth towards the operator, and controlled by with CNC controllers</p> <p>Working Space: Cubical</p> <p>Machining Area: Side surfaces</p> <p>Usage: Single setup machining on one or more surface</p> <p>Axes: Three Major Axes, X, Y, Z</p> <p>Additional Rotational Axis: 'a' or 'c'</p>	<p>Working Principle: Spindle is vertical to the work table and whose motion is directed up and down towards the operator and controlled by CNC controllers.</p> <p>Working Space: Cubical</p> <p>Machining Area: Top surfaces</p> <p>Usage: Single setup machining on one or more surfaces</p> <p>Axis: Three Major Axes, X, Y, Z</p> <p>Additional Rotational Axis: 'a' or 'b'</p>	<p>Working Principle: allows the machine to access the three basic co-ordinate faces of a part in addition to the other possible faces that may exist between using linear and rotary motions</p> <p>Working Space: Semi Spherical</p> <p>Machining Area Three basic coordinate faces and any existing face between them</p> <p>Usage: Single setup machining for multiple surfaces</p> <p>Axis: Three Major Axes X, Y, Z with combination any two rotary axis 'a-b', 'b-c' or 'c-a'.</p>	<p>Working Principle: Similar to a lathe with rotating chuck and carriage to carry the cutting tool parallel to the floor which is mounted on a slant bed.</p> <p>Working Space: Cylindrical</p> <p>Machining Area: Internal and external Cylindrical surfaces, and end of the cylindrical surface</p> <p>Usage: Single setup machining for multiple surfaces</p> <p>Axis: Linear X, Y, Z and Rotary 'c' combinations</p> <p>Types:</p> <ul style="list-style-type: none"> a) Two Axis <ul style="list-style-type: none"> • 1 Rotary + 1 Linear b) Three Axis <ul style="list-style-type: none"> • 1 Rotary + 1 Linear + 1 Turret head c) Four Axis <ul style="list-style-type: none"> • 1 Rotary + 2 Turret head d) Six Axis <ul style="list-style-type: none"> • 2 Rotary + 3 Turret heads 	<p>Working Principle: Turning centre with milling head are latest addition to Machining Centres, these machines have extra milling head spindle which move independent of the chuck of the turning centre.</p> <p>Working Space: Spherical</p> <p>Machining Area: All Faces possible with changer of holders in single set up.</p> <p>Usage: Single setup, complex machining requiring multiple settings.</p> <p>Axis: Linear X, Y, Z, and a, b, c combinations</p>
<p>Tool Holders:</p> <ul style="list-style-type: none"> • Basic structure of machining centre's tool holder consists of tool holder body, retention stud, collet and collet nut • Taper-flange types <ol style="list-style-type: none"> 1. V-flanges 2. BT-flanges 3. HSK flanges • Special purpose tool holder <ol style="list-style-type: none"> 1. Coolant through holder 2. Shrink fit holder 			<p>Tool holders:</p> <ul style="list-style-type: none"> • VDI tool holders types for turning centres <ul style="list-style-type: none"> <i>Round Serrated Shank</i> Holds tool straight to the axis of the holder <i>Square serrated Shank</i> Holds the tool perpendicular to the axis of the holder • Easy Clamping with precise, rigid and secure locking of the tool holder. 	

2.1 Contemporary Assessment

A modern machining centre is comparable to an orchestra as depicted in Figure 2.1. In the orchestra each artist adds an instrument and the master controls the harmonious integration. In the machining centre the controller controls the various shape changing functions in terms of relative motions. The machining centre can have few motion functions forming a simple machining centre or several motion functions forming a complex machining centre. Future developments may add even more functions. This aspect is well demonstrated in the cartoon used by Ingersoll Machine Tools [9].

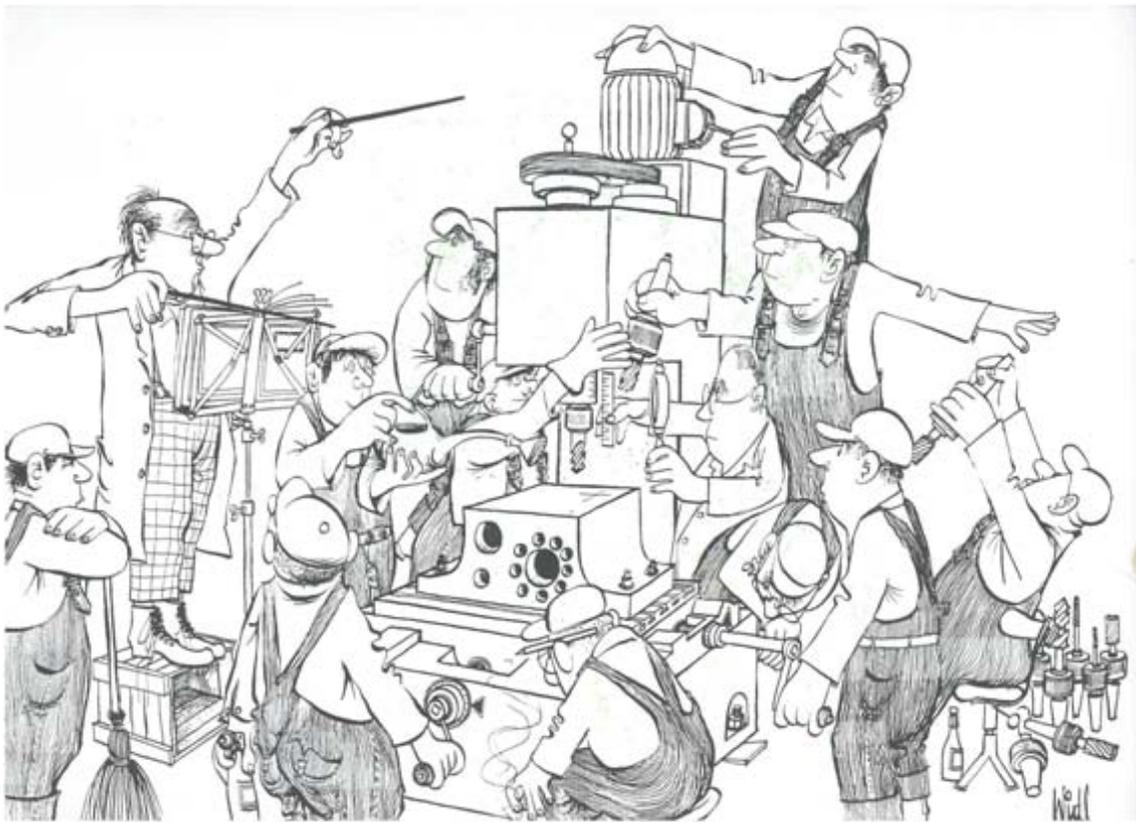


Figure 2.1: Cartoonist thought of control system on a machining centre [9]

From the preceding analyses it can be said that a modern machining centre can be described as a collection of motion function producing elements capable of producing several combinations to produce the relative motions necessary for specific cutting operations. Future developments would add more motion functions for further complex cutting. **Thus the code structure generated should not only be able to describe the existing motion functions but also should be flexible to add future addition of functions.**

2.2 Block Structure for Representing Machine Tools

Ito & Shinno [10, 11] state that a machine tool can be described as a combination of structural modules determined in accordance with the shape, dimension and machining condition of the work pieces to be machined. Such a 'Machine Tool Structure as a Whole' can be described as a Structural Pattern. They divide the flow of force in a machine tool into two portions namely (a) main flow (tool side) and (b) sub-flow (work-piece side). From this the structural configuration of the whole machine tool can be divided into two parts (a) sub-structure for the main-flow of force and (b) sub-structure for the sub-flow of force. Forces originate at the cutting point and propagate towards the foundation in both main and sub-flow. They are transferred across the donor and receiver modules until they reach the bed and hence the foundation. They continue to describe the forms the modules can take and their dimensions. The main contribution of this method to the research conducted by the author is the ability to describe a machine tool as a train of modules or blocks. The method is crucial for understanding the succeeding sections and therefore a worked example is given here to explain the process.

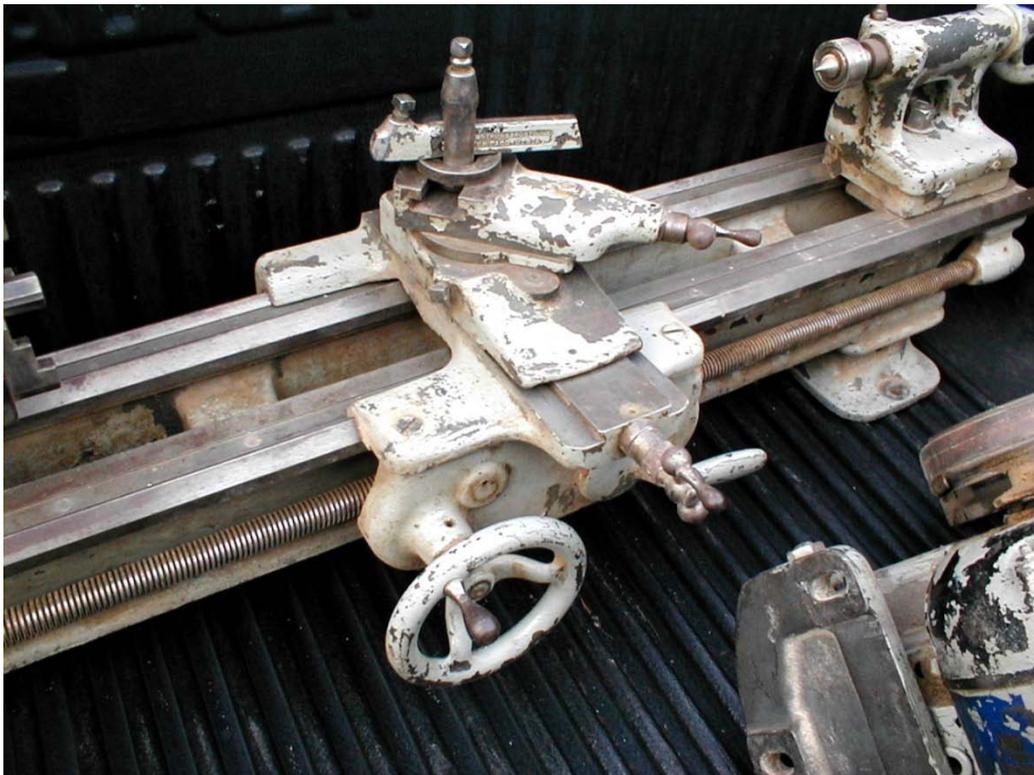


Figure 2.2: A Centre Lathe

Consider the lathe shown in Figure 2.2 which can be treated as an assemblage of two sets of moving parts, one carrying the work piece and the other carrying the tool, both of which are connected to the bed. Considering the tool, the moving parts are a) tool post b) turn table c) cross slide and d) carriage which are in turn connected to the stationary structure, the bed. This is the pattern of the Main Flow of Forces. Each of these is represented as a block. On the other side the chuck which carries the work piece is also connected to the same bed through the headstock. This forms the sub flow of forces. These parts can be stationary or perform either a) translatory motion (that follows linear path) or b) rotary motions (that follows circular path). There can be translatory or rotary motions along any of the three major axes. Each part with its respective motion along with axes direction can be represented as an individual block. The lathe can now be represented as a linkage of blocks as shown in Figure 2.3. The machining space (shaded part) is the area between the tool and the worktable, which is also represented as a block.

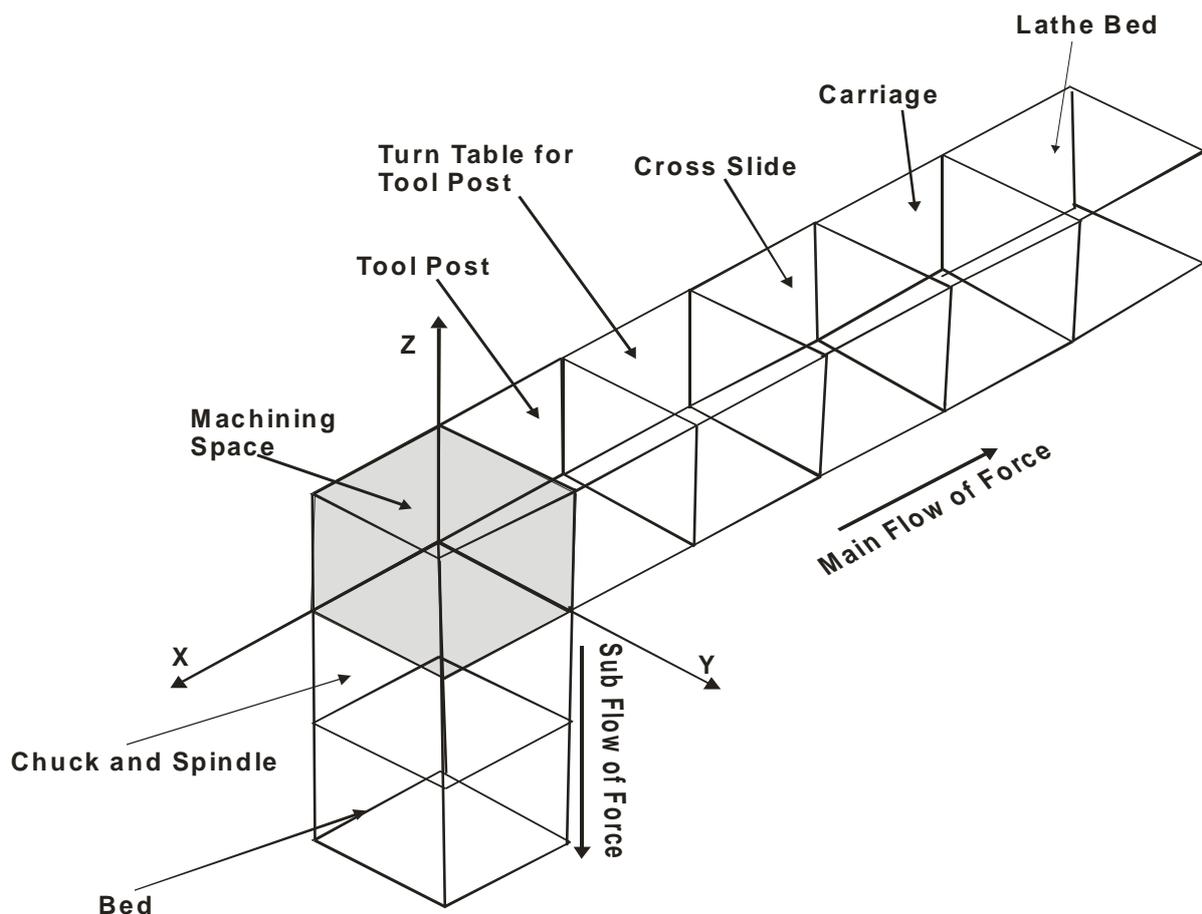


Figure 2.3: Block Structure of a Lathe

Block structure can be used to represent any machine tool that would consist of a single block to represent the workspace and numerous other blocks for the various motions performed on the machine tool. Number of blocks used in a representative block structure would vary with respect to number of moving and stationary parts in a machine tool.

2.3 Structural Representation in Sympathy with Block Structure Representation

Most of the work done in analysing structural layouts of machine tools has been done in the Soviet Union. In this section some of these methods have been described. Vragov's [5, 13] method, which is widely cited, is described first. *Portman's* [6] method of developing a numeric code is used is discussed second. Thirdly *Khomyakov* and *Davydov* [12, 14] proposed a code system at different levels of abstraction, which is followed by other research like *Voronovo* [7] who also worked in representing the machine tool with tool and pallet changing system.

2.3.1 Vragov's Method

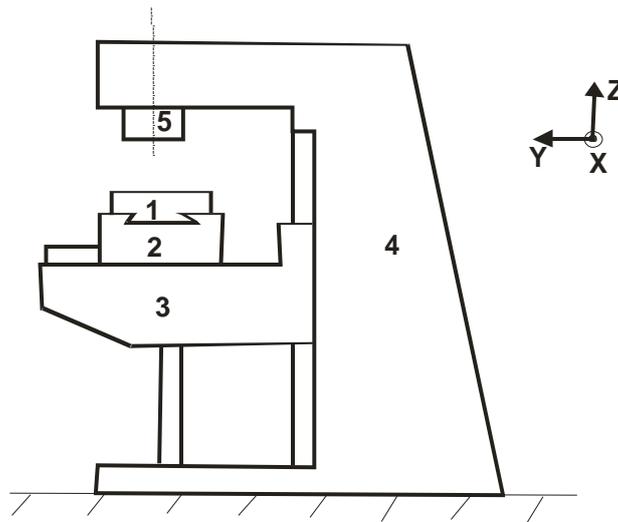


Figure 2.4: Vragov's Method Applied to a Milling Machine

Vargov [5, 13] method uses block structure, represented using symbols to describe the machine tool layouts. Considering the knee type milling machine shown in Figure 2.4 which has a cutting spindle attached on one end of the structure and three moving blocks on the other end of the fixed structure. The bed, the stationary block 4, is represent as '0', whilst three moving block 1,2,3 are represented by letters corresponding to motions of the axes (Right hand coordinate system nomenclature) X, Y and Z respectively. The cutting spindle,

block 5, rotating about the Z axis is represented as C. Thus the blocks involved can be represented as XYZOC.

The block structure not only includes information about forming and setting motion's direction but also number of spindles and its orientation towards work piece. Upper case letters are used to represent forming motion and lower case letters are used for auxiliary or setting motion. The main spindle in the knee type, milling machine is vertical to that of the worktable, which is represented using suffix 'v' for vertical and 'h' if horizontal to the block representing the spindle motion. More than one identical spindle is represented by numerical digit in front of the spindle block, while parallel linking is represented by '+' signs and separated by bracket. Linking of block of motion in a machine tool is without any symbol between them. The block carrying work piece is represented on the far left, whilst a block carrying the tool is represented on the far right with the consecutive blocks in middle. Thus the knee type, milling machine shown in Figure 2.4 is represented as 'XyzOC_v' in Figure 2.5. It is worth noting that motions along the Y axis and Z axis have been treated as auxiliary and motions represented by the X and C are treated as cutting motions. The suffix v along C indicates that the spindle is vertical.

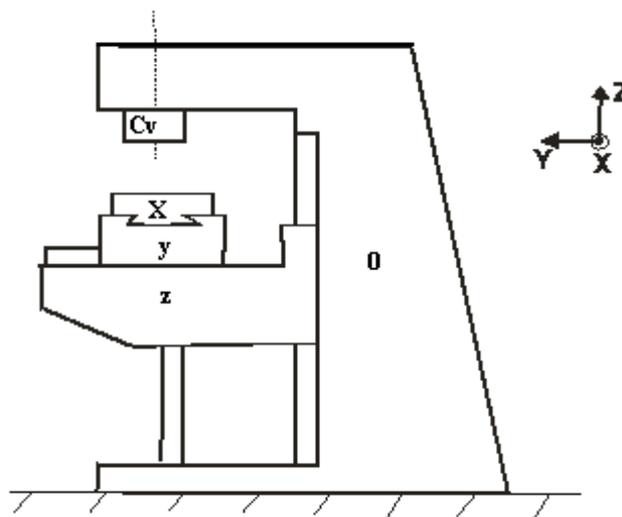


Figure 2.5: Vargov's representation of Xyz0C_v

Logical algebra is used to illustrate the consecutive linking of blocks as conjunction (AND function) and parallel linking as disjunction (OR), permitting machine tool structure of any complexity to be represented. An expression of combination of symbols thus represents (a) the structure of the machine layout, (b) the number and type of the forming and auxiliary

motions, (c) the order of linking and the (d) direction of the coordinate displacement of the blocks, (e) the distribution of elementary motions between the work piece and tool and, (f) the type of basic layout and the design arrangement of the blocks.

Considering the gantry type, milling machine as shown Figure 2.6 consist of a worktable connected to the base structure. Worktable performs the setting motions and has a translator motion along Y axis, which is in turn connected rotational axis along Z. The structure further consist of two cutting tool heads connected to structure a) to move along Z axis consisting of five spindle and b) to move along X axis consisting or five spindle head. This can be represented as “ $Y_c + 0ZC_{5v} + 0XA_{5h}$ ” as shown in Figure 2.7.

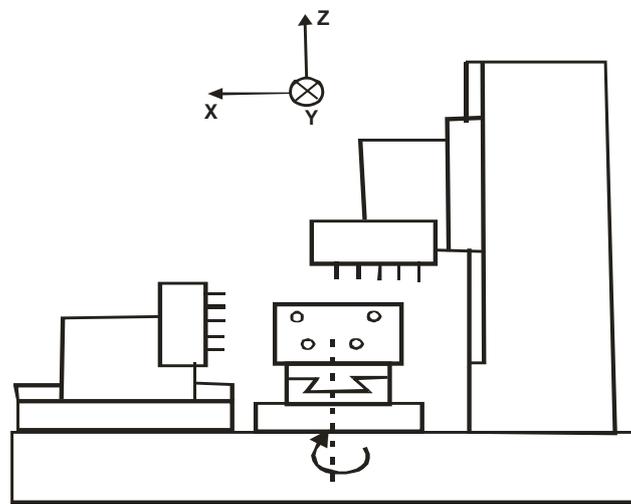
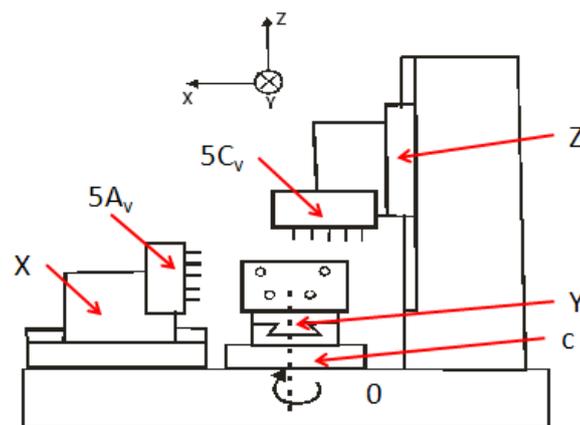


Figure 2.6: Gantry Milling Machine



$$Y_c + 0ZC_{5v} + 0XA_{5h}$$

Figure 2.7: Representation of a Gantry milling machine

2.3.2 Portman's Method

Portman [6] method described a machine tool using block structure and numerical symbols. Representation of numerical symbols is in continuous chain from the worktable to the cutting tool. The configuration is written in two stages.

The first one composes the 'code k ' for the machine tool form generating chain:

$$k = k_1 k_2 \dots k_n$$

In the second, the designation of the frame position is introduced

Writing the code k for the machine tool form generating chain

The code k for the machine tool form generating chain is given by

$$k = k_1 k_2 \dots k_n$$

Where

n is the number of moving links in the chain

k_1 to k_n is the designation according to Table 2.3 of the motion of the first link in the form generating chain with respect to the workpiece which is rigidly connected to the subassembly e.g. the work clamped to the spindle of a lathe.

In this manner k is a number with as many digits as there are moving subassemblies in the machine tool and each digit may assume value 1 to 6.

Table 2.3: Numeric Symbol representing motion

Symbol	Motion with respect to preceding link
1	Translatory along the X axis
2	Translatory along the Y axis
3	Translatory along the Z axis
4	Rotatory about X axis
5	Rotatory about Y axis
6	Rotatory about Z axis

Introducing the Fixed Frame

In the code describing the configuration fixed frame are represented using '0'. In the sequence of links from work piece to the tool if the fixed frame is the i^{th} then introduce a '0' at the i^{th} position. As an example consider a centre lathe shown in Figure 2.8.

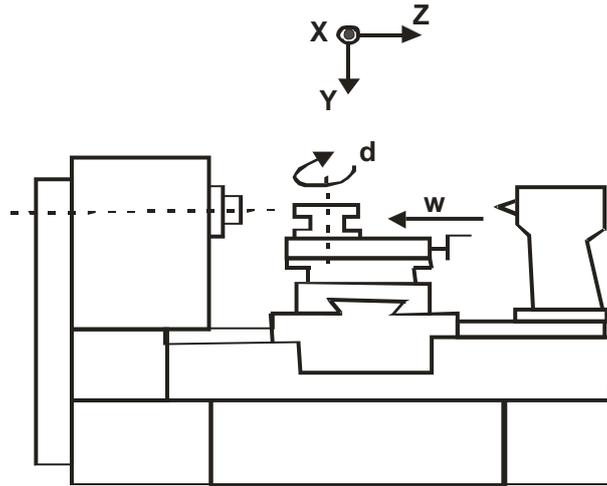


Figure 2.8: A Centre Lathe

The motions are (i) spindle rotation (ii) longitudinal translation of the saddle and (iii) cross travel of the tool. Therefore $n = 3$, and the fixed frame or bed is after the spindle. Therefore the lathe can be represented using the code is 6031 as shown in Figure 2.9.

$$k = 6031$$

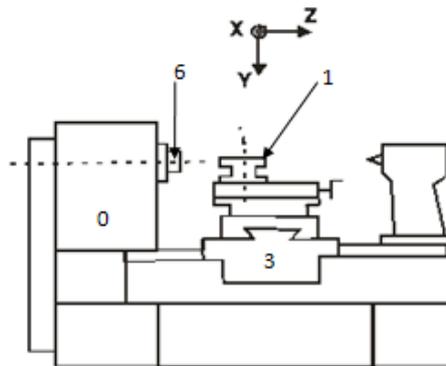


Figure 2.9: Representation of a Lathe by Portman's method 6031

2.3.3 Method by Khomyakov and Davydov

Khomyakov and Davydov [12, 14], proposes codes at several levels of abstraction and uses. The coordinate code described by them is comparable with other representations considered here. The coordinate code is a set of numerical symbol of coordinate motions and in general is of the form $K = K_1 - K_l - 0 - K_n$.

Where K_l - symbol for the l^{th} motion.

n – Number of motions realised in the layout

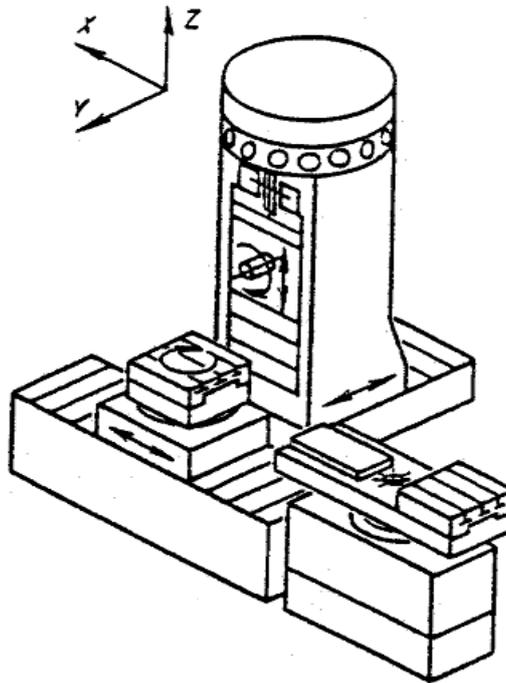


Figure 2.10: Layout of Model IR500PMF 4 [14]

K_i can have whole number values from 1 to 6; As with Portman's method Digits 1 to 3 represent rectilinear motions along the X, Y and Z directions and 4, 5 and 6 represent rotation relative to these axes. 0 is the divider between the tool and workpiece branches (fixed block). Symbol K_i is written with a superscript taking the values 0, 1 or 2 indicating the following:

- 0 – Setting motion (for example changing the tool or blank)
- 1 – Setting motion linked with machining (setting for machining a part with a given tool)
- 2 – Working motion needed for realizing the forming process.

The coordinate code thus represents the following properties of the layout:

- a. Number and types of motion provided (reciprocator or rotary)
- b. Orientation of the axes on or about which the motions are made
- c. Sequence of the motions
- d. Distribution among the tool branch and workpiece branch

Coordinate Code: for the machine IR500PMF 4 in Figure 2.10 is 532016 ($5^23^22^2 0 1^26^11^0$), which represents each motion of a block is defined by a number, where in turn 1,2,3 represents the Translator motions of X, Y, Z and 4,5,6 represents rotary motions along X,Y, Z respectively. Figure 2.11 represents the coordinate code of the IR500PMF 4. Non moving block of the element is represented as '0'. Further the joints between the motions can be used to represent them as forming or setting motions as postscripts of 2 and 1 respectively.

Table 2.4: IRM500PMF representation Code

Coordinate Code	532016 ($5^23^22^2 0 1^26^11^0$)
Block Code	800 312/201 312/101 123/101 13-2/0/101 231/602 123/501 231/900 123
Element Code	800 312/406 312/201 312/401 123/101 123 H00500/407 123/101 13 – 2 H00500/403 312/0/403 231/101 231 H00500/402 123/602 123/405 123/301 123/402 123.501
Design Code *represent's the joint providing motion between Y axis to X axis 101 13-2 B:Y-1330 Z – 0695 H00500 R:00780 01145/ 403 312 B:Y – 2525 Z – 0892 P070000 R:01230 00544 12245/ 0/ 403 231 B:X – 0960 Y00455 Z – 0892 P070000 R:01100 00544 01920 101 231 B:X00250 Y00470 Z – 0400 H005000 R:00520 00800

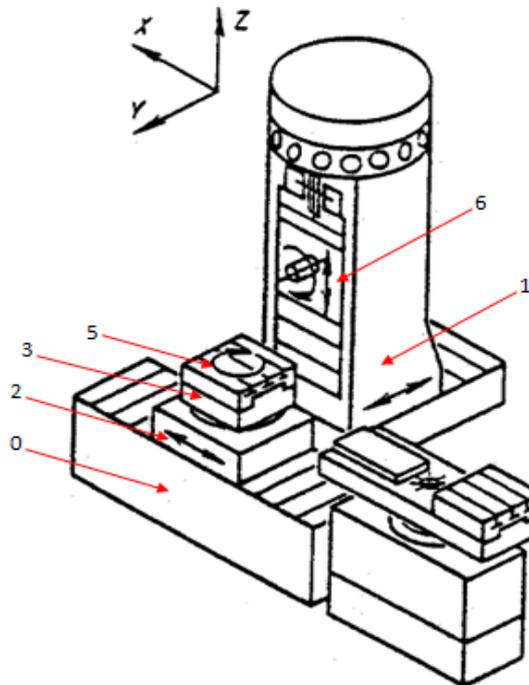


Figure 2.11: Representation of IR500MPF by Khomyakov $532016 (5^23^22^2 0 1^26^11^0)$

Block Code: includes further information to that of coordinate code, like a) information consisting of position in space for the joint faces b) mounting plane and c) length of moving joints.

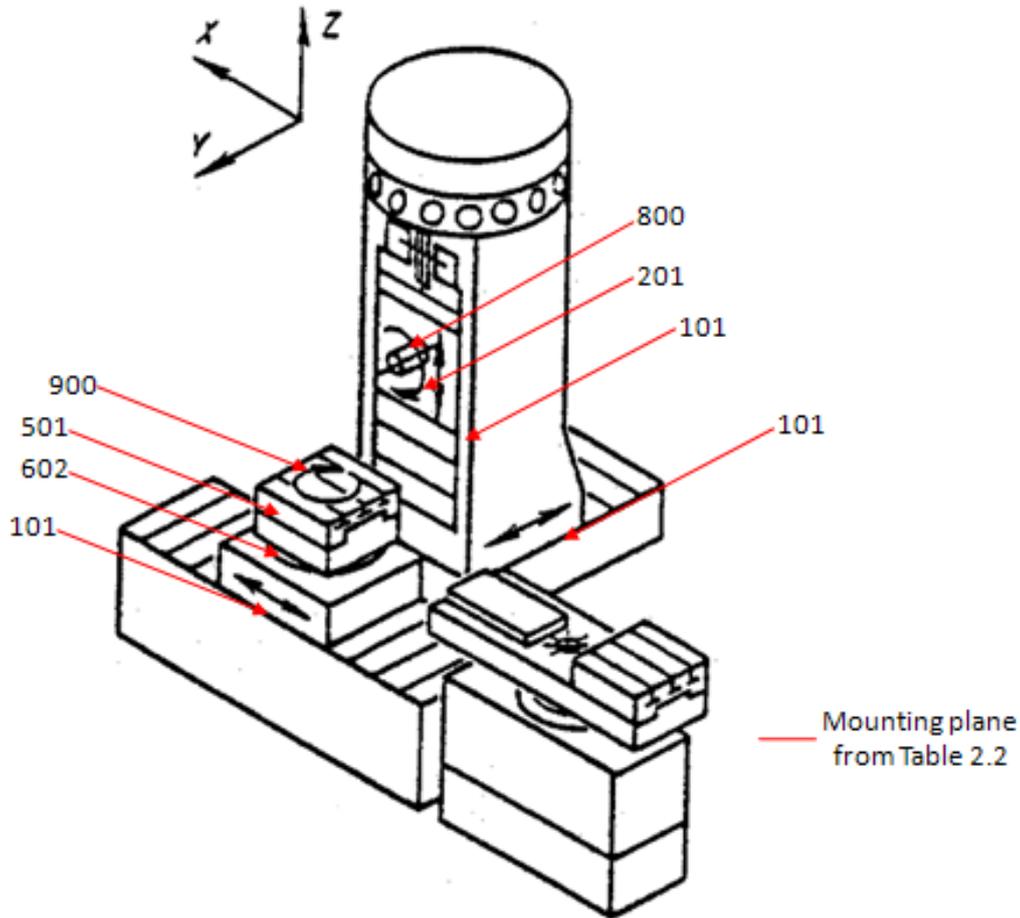


Figure 2.12: Representation of IR500MPF with its mounting plane

Consider the block code from Figure 2.11 “800 312/201 312/101 123/101 13-2/0/101 231/602 123/501 231/900 123”. The code consists of pairs of numeric parts, which are separated with a division symbol. Each pair represents a block, 800 and 900 represents the tool and blank respectively, where the first part of the pair represents the mounting plane is found from Table 2.5 and the next part represents the length of contact being determined by the moving part. Figure 2.12 represents the block code of IR500MPF.

Table 2.5: Layout Elements [12]

A		B		Type of layout element						
Joints with rectilinear motion	Moving	1		01	02	03	04	05	...	
	Conditionally moving	5								
Joints with rotary motion	Moving	2		01	02	03	04		...	
	Conditionally moving	6								
Fixed joints	J		Type of layout element							
			01 (Contact in plane)		02 (Contact on cylindrical face)			...		
Parts of LCS	4		Type of layout element							
			01	02	03	04	05	06	07	08

Element Code: consist of further smaller and sub divided elements from block code that constitutes a) type of joint and b) plane to which it is connected. Consider the joint 602 to 501, in particular the last block from the block code which is represented as 602 123/405 123/301 123/402 123/ 501 231 in element code from Table 2.5. The element code consists of details of joints which are represented in two types a) '4' for load carrying system; in addition 02 represents LCS square and 05 represents cylinder and b)'3' for fixed system; in addition 01 for contact in plane and 02 for cylindrical plane. The element H represents the maximum rectilinear motion by the block in millimetre or rotation angle depending on the type of motion.

Design code: Consist of sub-elements from the element code like, type of slide, material of the housing, weight of the element (G), coordinate vector of the centre of gravity (b), vector of the layout (r). Table 1 represents the part of the design code for the coordinate code of 201, with all the sub-element details.

Analysis of structural layouts in sections 2.7 to 2.9 shows that the structural layout of rapidly changing machine tools can be described as an assemblage of blocks and they can be represented as an alphanumeric code. The codes in its simplest level can be a string of characters. But there can be codes describing the machine tool at several different levels of abstraction.

2.4 Structural Configuration of Machine Tools – The Design Methodology

Ito and Shinno [10, 11, 15, 16] have developed a design methodology for the modular construction of machine tools based on the block system. It is a computer Aided system to construct a machine tool structure as a whole integrating structural modules. It performs two functions (a) Generating Structural Configuration and (b) Performing Structural Analysis. The methodology described in Figure 2.13 in the form of a flow chart. The right hand side of the flow chart shows that the movement function is the fundamental key for deciding the number of blocks, the starting block and all other details. In the left hand side the packaging of the modules to form a functioning machine and its rigidity related characteristics are determined. The methodology is very much suited for the design of a modern machine tool.

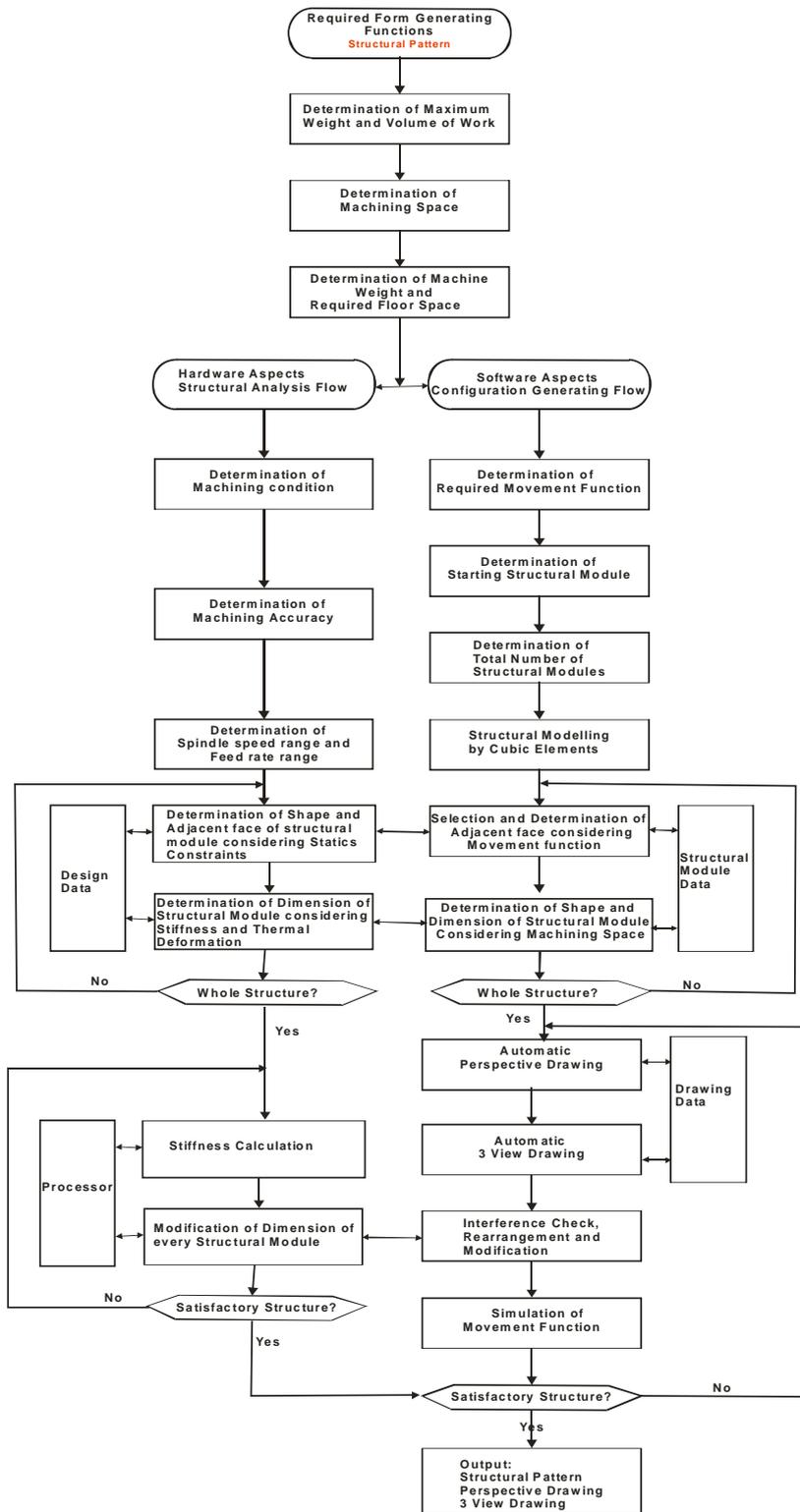


Figure 2.13: Flow Chart of Ito and Shino's Methodology

2.5 Chapter summary

The survey is carried out to understand the frontiers of existing technology and to formulate the basis for work carried out in this research. Three major findings can be said as summary of the survey:

1. Development of Machine tools started from the 18th Century were analysed under the five categories (a) development in the processes (b) mechanical synchronisation (c) development of cutting tools and coolants (d) early NC and automation and (e) development of controls and controllers. These developments led to the creation of Machining Centres capable of providing many operations in one machine. The trend in development is seen as adding more cutting functions to make the Machine more sophisticated. The preceding analyses led to the description of a modern machining centre as a collection of motion-function producing elements, capable of producing several combinations to produce the relative motions necessary for specific cutting operations. Future developments would add more motion-functions for further complex cuttings. **Thus the code structure generated should not only be able to describe the existing motion functions but also should be flexible to add future addition of functions.**
2. Block structure developed by the soviet scientists is seen as a useful and powerful way of describing machine tool structures. The foundation of these methods is the division of a Machine Tool into two sections as the main flow of forces and sub flow or forces. *Vargov* represented machine tool as combination of motions, representing each motion as a block and used Boolean algebra to represent parallel motion. Later *Voronov* developed a four part coding system to represent the machine tool that included tool and work piece changing system. *Portman* configured machine tool as a numerical code based on analysis of form generation process *Khomyakov* and *Davydov* developed a multi level coding system to describe different aspects of a machine tool. The target uses of these codes were not clear and are not recorded in the public domain. **The developments though not complete established the hypothesis that an Alphanumeric Code can describe a Machine Tool.**
3. Shino and Ito have presented a design methodology for a Machine Tool. This highlights that the primary step is to provide the motion functions in block structure, which is then enhanced by structural design methods for mechanical properties. This

supports the view that future machines can have more blocks providing more complex motion functions. It gives the notion that an Alphanumeric Code structure developed should be capable of having further addition of motion functions.

Chapter 3 – Literature Survey – Machining

3.0 Introduction

Machining operation is possible, only when there is a machine tool and there is a work. Machining is the production of desired geometric shapes on the surface of a finished work piece by removing material from a raw stock. Chapter 2 investigated the Machine Tool side of Machining. This chapter investigates the workpiece side, the machining or creation of feature side of the operation. Computer Aided Engineering identifies Feature Based Machining as the efficient way for handling machining operations. In this context a feature can be visualised as a collection of basic geometric entities such as vertices, edges, surfaces and solid lumps, which as whole gives an engineering meaning. Feature as defined by Jami Shah [17] is a “*Stereotypical knowledge structures embedded in cognitive process in design, analysis, planning and all other engineering activities; features are necessarily view points and application dependent*”. This chapter investigates Feature Based Machining to understand the state of the art and to integrate it within the process of matching machines with work.

In Computer Aided Engineering a Computer model of an object is created and this master model is used by various applications such as mechanism or motion analysis, Finite Element Analysis, Machining planning, packaging etc. CAE packages use what is known as a set of design features to create feature instances and a master model is an assemblage of design feature instances present in the object under consideration. As an example consider the object shown Figure 3.1. This has two features, a protrusion and a hole. The master model or the design model is shown in Figure 3.1(d) as a model tree produced by Pro/Engineer. Pro/Engineer, using the design features, has created all geometric features describing the object. However when the machining of this component is considered these geometric details are grouped differently into several machining features as explained in Figure 3.2.

Machining of the component requires twelve machining operations or features to be completed. Their details can be summarised as: *Features 1, 2, 3, 7*: requiring removal of rectangular volume of material, as a result of which two surfaces would be formed on the raw stock. *Features 4, 9, 10*: requires removal of rectangular volume of material, as a result of which single surfaces would be formed on the raw stock. *Feature 8*: requires removal of material, which would form a semi cylindrical surface. *Features 11, 12*: require removal of cylindrical volume of material, forming full cylindrical surfaces. Similar analyses were carried out on several components and their summaries are given in Appendix C. From the analyses it became evident that with increasing complexity of the work-piece in high value added components, the number of machining operations required, increased significantly. Each machining operation had its own complexity. The steps that were considered before machining are a) Identifying Machining operations, b) Selection and Preparation of Raw Stock, c) Grouping the Machining operations and d) Sequencing the Machining operations. As the complexity and number of machining operation increased, ascertaining, verifying and sequencing the machining operations manually, became almost impossible. Also it became clear that the type of operations performed were similar in many cases.

The task in feature based machining is to identify and define the machining features from the design or master model described by the design feature instances. Several researchers have developed different methods to identify machining features and automate the identification process. For easy comprehension they can be classified into Graph, Rule, Volume, Hint, Syntactic pattern, Template matching, Hybrid and Artificial Neural Network based systems. In this work they are categorised into four major groups based on the type of integration with manufacturability a) Geometry based system providing intrinsic details of basic geometry forms b) Feature based system providing details of pre-defined templates of features or geometry c) Application Programming Interface systems that interact with CAD model to extract the required details and d) various combination of the above three systems. The following sections review them.

3.1 Geometry Based Approaches

Solid models are described using geometric boundaries for its representation; the boundary representation data structures can be viewed as graph structure. Graph, Hint and Rule based can be grouped into geometry-based approach as they all use the geometric entities within shapes such as vertices, edges and faces to identify the features.

3.1.1 Graph Matching

Boundary representation of a part can be treated as a graph structure, where faces are considered as nodes of the graph and face-face relationships form the arcs of the graph. The advantages of the graph representation are that there are well-established techniques of graph algorithms easily adaptable to feature recognition.

Figure 3.1 represents a graph notation of a rectangular pocket. As seen in the Figure 3.3a, the pocket has faces 2, 3, 4, and 5 and bottom face 1. Figure 3.3b shows the neighbourhood relationship. Node 1 is connected to nodes 2, 3, 4 and 5 representing the connection between face 1 and the face 2, 3, 4 and 5. The line connecting nodes 2 and 3 represents the connection between the face 2 and 3. In a similar fashion the line connecting the nodes 3 and 4, 4 and 5, 5 and 2 represents the connection between the respective faces. The top face 6 is connected to faces 2, 3, 4 and 5 and these are connected by line in the graph. In the similar manner the entire solid model can be connected by line in the graph. In the similar manner the entire solid model can be represented using a graph structure. These graphs are matched with the topological graph structures of the predefined recognisable feature set. The features present in the solid model can thus be identified using the graph matching.

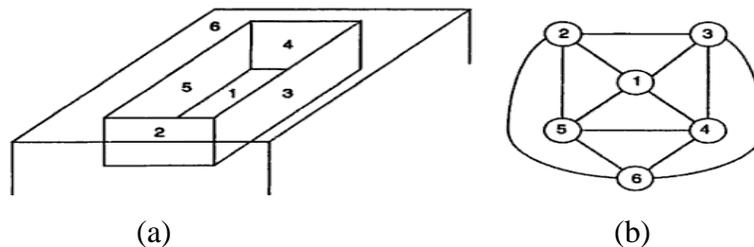


Figure 3.3: Face Relation

Most published works on graph based feature recognition are related to recognition of relatively simple prismatic features (holes, slots, bosses, pockets) even these are ambiguous because similar graph can be interpreted into different features.

3.1.2 AAG

An early graph based machining features recognition method using underlying boundary representation model was developed by Joshi and Chang [20]. Similar to the graph notation described earlier the AAG also uses the faces as node and edges as arcs. However the AAG stores the additional information to specify whether the edges are concave or convex. Features are recognised by searching for sub-graphs corresponding to predefined features in the attributed adjacency graph.

Figure 3.4 shows the AAG graph segment of a slot feature defined by the faces (F_1 , F_2 and F_3). The graph segment for the slot is shown in Figure 3.4b. In this method a concave arc edge is denoted by '0' and convex edge by '1'. The edge connecting F_1 and F_2 is a concave and the face connecting the edge F_2 and F_3 is convex. Graph based method strongly relied on topological patterns rather than geometry of the models due to which it failed to account for manufacturability of the recognizable features.

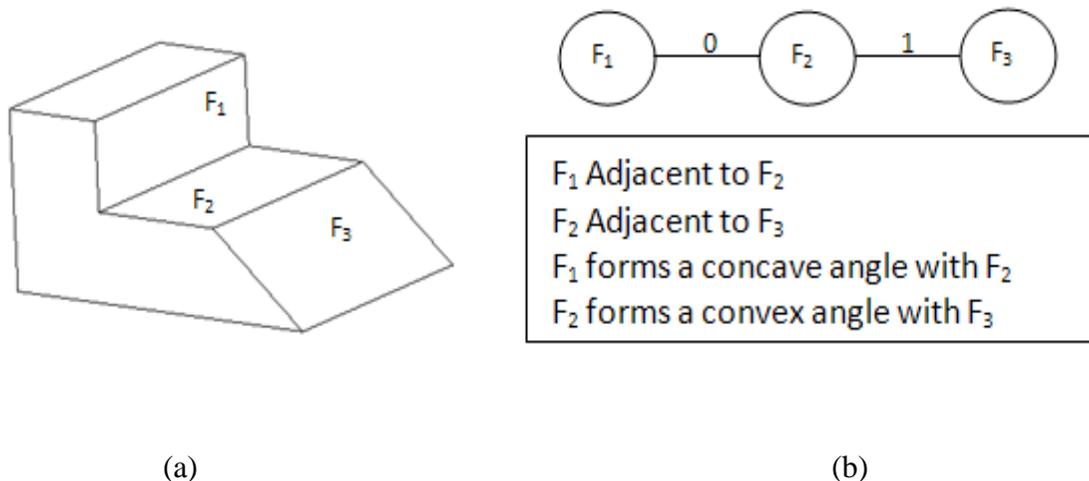


Figure 3.4: Feature Recognition using AAG

3.1.3 EAAG

Extended attributed adjacency graph (EAAG) developed by [21] incorporated additional information in the graph structure with respect to a) number of edges on the face, b) the direction of the faces c) orientation of the face and d) by adding virtual link to corresponding entities lost in interaction. This additional information aids further processing such as recognition of interacting features. Marefat et. al., [21-23] attempted to treat general feature interactions based on their new method called “Generated-and-test paradigm and virtual link” concept which was extension of EAAG to include some geometric constraints on the orientation of the feature faces. However this approach required development of further algorithm to make it an implementable system.

3.1.4 Hint Based

Hints are geometric tracers for the presence of specific features, such as presences of an axis indicates existence of a hole or cylindrical protrusion. In the hint-based approach, features are built from hints by searching the boundary representation of the part. Only hints, not full-fledged features, are found, at first and then the missing portions of the feature are reconstructed. Meeran [24-26] used Hint and Graphed based approaches to search for “minimal indispensable portion of feature’s boundary” called hints, rather than complete feature. Hint based approach streamlines identification of intersecting features by recognising the presence of one of them by the traces left behind. For example, presence of two opposing planar faces is a hint for potential existence of a slot feature or a thread can be hinted for hole. Vandenbrande & Requicha [27-29] also developed a hint based feature recognition approach that undertakes the feature recognition in four steps. Firstly feature hints are generated by searching for characteristic combinations of part faces on the solid model, secondly the feature hints are classified into promising, unpromising and rejected hints, thirdly the promising hints are processed by a “feature completer” to generate the actual features, and finally a verification step is performed to ensure that the recognised features are valid. Vandenbrande and Requicha claim that their approach is better at recognising interacting features that earlier work couldn’t, but they are still limited to 2.5-D swept features, and mostly prismatic parts. Hints are not

necessarily restricted to the part geometry. The drawback of the system was also that the prismatic cavities were classified as pockets, resulting in machining some other feature like T-slots as the method were partially efficient. Hint based feature recognition is quite promising for recognizing intersecting features, but it is limited to predefined features and hints.

3.1.5 Rule Based

Rule-based methods identify a feature, based on pre-defined rules that are characteristic to individual features [30]. The entities expressed in the rule are typically the boundary elements: faces, edges, loops and vertices. Constraint operators typically included parallel, perpendicular, adjacent, equal, concave and convex relationships or conditions that these entities must satisfy to define a particular feature. Preiss and Kaplansky [31] developed a rule-based algorithm that identified individual cutting operations by goal-driven search. Choi *et al.* [32] used pattern-matching technique to define a 3D boundary file data structure for representing the solid model. Henderson & Anderson [33] converted B-rep solid models and feature definitions into facts and rules of expert system. The reasoning mechanism of Prolong searches through the facts to recognize features according to the rules. Nnaji & Liu [34] developed a system that extracts features relevant to assembly and machining from a CSG-based CAD system with the ability to transform a CSG structure into a B-rep. Raymond *et al.* [35] presented an algorithm that uses an octree representation of a B-rep for identifying assembly features. Their algorithm is used to support the geometric reasoning required to locate assembly features on disjoint bodies.

3.1.6 Summary Finding

Thus Graph, AAG, EAAG, Hint and Rule based systems used lower level geometric data like number of edges, vertex and faces to identify partial set of machining features. These methods were not efficient enough for complex real world parts due to extensive use of

Boolean operation and Artificial Intelligent (AI) languages for feature recognition. Summarising the outcomes i) not all necessary graph links are found and at times incorrect link [21] are identified and ii) the incorrect feature hypotheses have to be eliminated [36]. Geometry based systems did not see much maturity; their implementation in wide and varied domains are yet to be seen. This was due to larger proportion of manufacturability related data, such as feature constrains, feature details, Tool Approach Direction (TAD) and dimensional details are yet to be identified or lost in the process. Table 3.1 summarises the capability of individual geometry based approach.

Table 3.1: Geometry Based Approaches

Authors	Feature Recognition Method	Category	Full Set of Machining Features Identified	3D features	2.5D /2D features	Partial Set of Machining Features Identified	Identification of Intersecting features	Compound / Array Features	Automatic Feature Recognition	Primary Factor for feature recognition		Tool Approach Direction (TAD)	Feature created by Design		Dimensional Details of Machining Feature	Adequacy Check of machining feature for manufacturing	Integration with CAPP	Integration with CAM	Standard of Exchange STEP-224	Heuristics Algorithm	Implemented Method	Selection of Available Machine tools	Stand alone Program/Software	Integration with CAD System	Representation of features	
										Surface	Edges		Destruction	Synthesis												
<i>Joshi & Chang</i>	Graph	Geometric Based		X		X				X			X			X				X	X		X			
<i>Marefat and Kashyap</i>	EAAG			X		X	X			X				X			X				X	X		X		
<i>Meeran</i>	Hint				X	X	X		X		X			X			X				X	X		X		
<i>Vandenbrande & Requicha</i>	Hint			X	X	X	X		X		X			X			X				X	X		X		
<i>Preiss & Kaplansky</i>	Rule			X		X			X		X			X			X				X	X		X		
<i>Choi et al</i>	Rule			X		X					X			X			X				X	X		X		
<i>Nnaji & Liu</i>	Rule			X		X			X		X			X			X				X	X		X		

3.2 Feature Based Approaches

Feature is a high level entity containing geometric and topologic information of the entities (vertices, edges and faces) that form the feature. Part model is formed as an assemble-large of feature instances. Features are application dependent as said by Shah [17-19], like machining features, design features, and inspection feature etc., Machining features which is the main focus of this thesis has been defined both as surfaces and as volumetric features.

3.2.1 Volume based

The volume decomposition approach decomposes the input model into a set of primitive volumes and then manipulates them to identify specific features instance. The approach is based on the idea of finding the materials that must be removed from a raw stock to produce a part. Figure 3.5 lists the various volumes to be removed from a stock in arriving at the end model. Kyprianou [37] initially developed the volume based approach, using B-rep graph into hierarchical face-set data structures which was then analysed using algorithm based on feature grammars. Kim [38] developed a convex decomposition method for feature recognition from solid models following on from earlier work by Kyprianou [37] and Kim et al., [38] uses a technique called alternating sum of volumes with partitioning (ASVP) to a B-rep solid model to recognise volumetric form features from the model. In this approach decomposing the solid part into a hierarchical structure of convex elements, where each element represents a volumetric feature on the part performing the feature recognition. The main problem with volume-decomposition methods is that the operations in each step do not guarantee success in the identification of the features, and on completion it may not be possible to generate a feasible model totally using features.

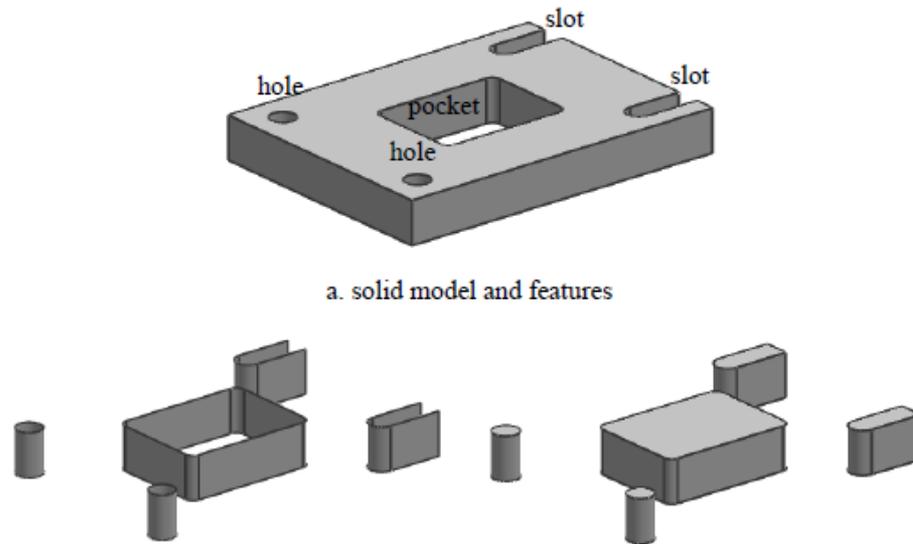


Figure 3.5: Surface and Volumetric representation of features

This approach is also only applicable to polyhedral parts with planar faces, so curves have to be approximated to straight lines before processing. Woo's [39] feature recognition, which was among earliest methods, uses Alternating Sums of Volumes (ASV). An efficient method was developed by Little & Clark [40] as compared to the previous work, but their implementation was limited to feature recognition. Most systems [41, 42] are limited to 2.5D features with constant cross sections that are extruded along the direction of their depth.

3.2.2 MRSEV

Gupta & Kramer [43] developed a library of Material Removal Shape Element Volumes (MRSEVs) as means of categorising the shapes of volumes to be removed by machining operations on a 3-axis machining centre. MRSEVs were defined using the EXPRESS modelling programming language and STEP. MRSEV hierarchy provides a framework for describing a large class of entities interest to machining. Each entity type has a number of necessary and optional attributes. MRSEV instance have been used for applications such as NC program generation. Figure 3.6 shows the MRSEV for a defined feature set. Kramer's main MRSEV types include linear, swept, edge-cut, ramps and rotational pocket features. Regli et al., [44, 45] proposed an approach that addressed a class of machine-able features expressed as MRSEV (Material removal shape element volumes), as an extend work to Kramer's.

Predefined attributes were used to match and identify specific machining feature with help of graph-based methods.

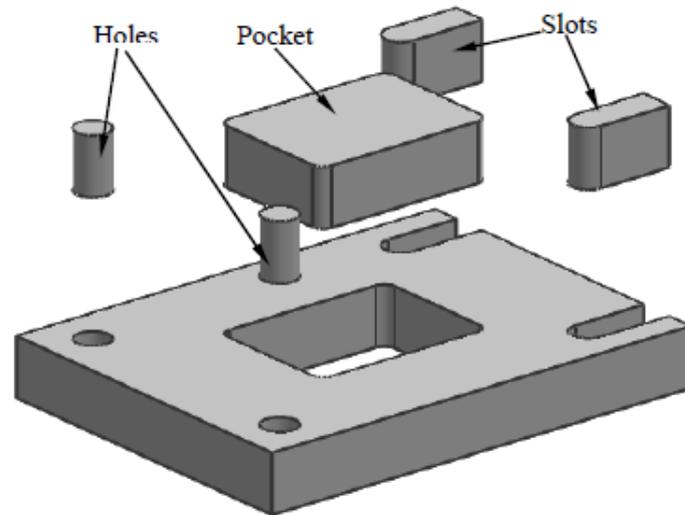


Figure 3.6: MRSEV features

Woo [46] and Huang [47] have focused on particularly domain of machining features, using the same principles of volume based method. Li & Wang [48] considered feature sequencing and operation sequencing which were restricted to prismatic parts no integration towards machining. Feature based methods are efficient at dealing with arbitrary feature interactions and generating multiple interpretations of features.

3.2.3 STEP based

Due to the nature of most neutral files such as ACIS, PARASOLID and IGES, they only employ the boundary representation model for communication or translation purposes between dissimilar CAD systems. Naser et al. [49] and Aslan et al. [50] developed methods to identify machining feature from a standard data file (STL, STEP, IGES) input and translate the information into CAM readable file with manufacturing information. These systems lacked the ability to recognize intersecting features due to loss of geometric data when transferred into a neutral file format. STEP standard is a neutral file format that utilizes feature technology as they key for file transfer and sharing. Using STEP file, data required for the NC programming such as features details are gathered.

The disadvantages of feature-based method however can be summarised as follows as shown in Table 3.2:

- i) Computational complexity,
- ii) Inability to generate non-convex delta machining features in some cases
- iii) Inability to recognize full set of machining features
- iv) Human intervention was required for intersecting features
- v) Dimensional details and TAD required for machining were included

The optimistic outcomes of feature based approach was that it used

- i) Volume based method,
- ii) Highlighted the need for a standard data format.
- iii) Research were focused towards machining features rather than general feature

Table 3.2: Feature Based Approaches

Authors	Feature Recognition Method	Category	Full Set of Machining Features Identified	3D features	2.5D /2D features	Partial Set of Machining Features Identified	Identification of Intersecting features	Compound / Array Features	Automatic Feature Recognition	Primary Factor for feature recognition		Tool Approach Direction (TAD)	Feature created by Design		Dimensional Details of Machining Feature	Adequacy Check of machining feature for manufacturing	Integration with CAPP	Integration with CAM	Standard of Exchange STEP-224	Heuristics Algorithm	Implemented Method	Selection of Available Machine tools	Stand alone Program/Software	Integration with CAD System	Representation of features	
										Surface	Edges		Destruction	Synthesis												
<i>Kim</i>	Convex Hull	Feature Based		X		X			X	X			X				X			X	X		X			
<i>Kyprianou</i>	ASVP			X		X	X		X	X			X					X			X	X		X		
<i>Y Woo & H Sakurai</i>	Volume Decomposition			X		X	X		X	X			X					X			X	X				
<i>G Little, DER Clark et al</i>	Delta Volume Decomposition			X		X			X	X			X					X			X	X		X		
<i>Kramer</i>	MRSEV			X		X			X	X			X					X			X	X		X		
<i>Regli and Nau</i>	MRSEV			X		X	X		X	X			X					X			X	X		X		
<i>Z Liu & L Wang</i>	Machining Feature			X		X	X		X	X		X		X						X	X		X			
<i>Naser et al</i>	STEP			X		X			X	X	X			X				X			X	X		X		
<i>Aslan et al</i>	STEP			X		X			X	X	X			X				X			X	X		X		

3.3 Application Programming Interface Approaches

Application Programming Interface (API) picked up movement with development in CAD system, providing application interface to retrieve the required data from the CAD Design. This provided easy interface for features recognition methods. In API platform-dependent approach, both the creation of the CAD model and the feature recognition are done in the same CAD platform. Individual design feature information is obtained via programming in the API provided by the CAD modeller. The advantages of API approach are, a) Easy access to generic features in the library, b) ability to retrieve geometry and topology data of the specific feature instances, c) Exploitation of the built in functions (API) from within the solid modeller to facilitate the application of the feature recognition rules.

Lee & Kim [51] extracted machining features data from a feature-based CAD model, which was based on an integrated geometric modelling approach system that supported both feature-based modelling and features recognition. Lee and Kim presented an approach for incrementally extracting machining features from a feature based design model as a design progress. The proposed approach utilizes both feature and geometric information of the feature instance for feature mapping. Hence it works well for mapping design features, including protrusion, transition and interacting features, into machining features. Interacting features can be effectively handled by the generic naming scheme that manages all the merged and split faces

Here the system is capable of handling the majority of complex features, however due to high dependence on the design driven approach, it was not successful in extracting all application specific features domains. Woo and Sakurai [46] presented a system for recognizing a set of machining (or maximal) features in a designed part. This was done by decomposing the delta volume, which was the machine-able volume from the stock in arriving at the part. Huang et al. [47, 52] studied the decomposition and combination of delta volumes for converting features. Their efforts exploited the robustness of the platform-dependent tools in solving the problems.

Li et al. [53] proposed a methodology for recognizing manufacturing features from a design-by-feature solid modeller. They analysed design feature's using 2D profile to convert into

manufacturing features. The limitations of their work were due to the difficulty in creating 2D profiles for complex features. Sadaiah et al. [54] identified the feature as the input for the computer-aided process planning (CAPP). This system records individual feature information of models designed in SolidWork, a 3D CAD modeller. In this research, the designer's interaction with the solid modeller was reflected into a text file.

The syntactic pattern recognition approach uses the semantic primitives for part analysis. The structured information is used to create a description and a classification of the part. Arivazhagan, et al. [55] developed Machine-able Volume Identifiers (MVI) and used syntactic pattern strings stored in database to check the generated strings of the features. This covered only feature like Step (through, blind & with corner conditions), Slot (through, blind & with corners conditions), Pocket (Through, blind & corner conditions), Hole and Chamfer; further details required for machining was not implemented.

Projective feature developed by Lee et al. [56] felt the need for precedence relation among features from CAD depending on the location of the feature and its machining restrictions. This was a development of Tseng & Joshi's [57] approach using API; the outcome was limited to 2.5D features. This method was focussed towards the process-planning algorithm and not towards machining.

Prabhakar & Henderson [58] were the pioneers in using neural network based feature recognition algorithms in feature recognition. The input to the system is a face adjacency matrix, which consists of relationships between faces, with each row of matrix containing information related to a face. The two major characteristics of Neural Network are learning and recalling. Learning is the process of adjusting the connection weights to produce the desired output. Recall is the process of providing an output for a given input in accordance with-neural weight structure. The application of Neural Network Based feature recognition has some conflicts due to interacting features such as blind slots and non standard type features. This is due to face adjacency matrix not containing all geometric information to define the features of same topology.

Artificial Neural Network (ANN) based feature recognition techniques were developed by Ding & Yue [59] and various other researchers [58, 60-62]. ANN techniques have become advantageous because they reduce some drawbacks like limited feature recognition and additional heuristic rules need of that of geometry and feature based systems. However ANN based systems are not matured enough to identify the entire machining features, but have the capabilities to identify geometrical and manufacturing information such as feature class, dimension & tolerance, TAD and feature relationships.

API and ANN approaches identified the user-defined features, but did not meet the basic need for feature recognition towards integration of CAD/CAM. The major drawbacks of the API based systems can be summarised as shown in Table 3.3:

- i) Input representation of features were ambiguous
- ii) Features were not unique and
- iii) Large size of matrix to define a features restrict the capability of computing

Due these drawbacks they were considered non effective and non efficient in many instances. API programming eliminated most-problems encountered by previous methods. However it's lack of ability to identify intersecting features and ambiguity of input representation limited its application. It also failed to cater the full requirements of a machining process, lacking in vital information needed, such as feature class, feature interaction, dimensions and tool approach direction. Though API is in forefront of present research work in identifying machining features from a CAD based system, the elimination of its drawbacks will project it as a viable alternate.

Table 3.3: Application Programming Interface Approaches

Authors	Feature Recognition Method	Category	Full Set of Machining Features Identified	3D features	2.5D /2D features	Partial Set of Machining Features Identified	Identification of Intersecting features	Compound / Array Features	Automatic Feature Recognition	Primary Factor for feature recognition		Tool Approach Direction (TAD)	Feature created by Design		Dimensional Details of Machining Feature	Adequacy Check of machining feature for manufacturing	Integration with CAPP	Integration with CAM	Standard of Exchange STEP-224	Heuristics Algorithm	Implemented Method	Selection of Available Machine tools	Stand alone Program/Software	Integration with CAD System	Representation of features	
										Surface	Edges		Destruction	Synthesis												
<i>Lee & Kim</i>	Feature Based	Application Program Interface		X		X			X	X			X							X	X		X			
<i>Woo & Sakurai</i>	Machining			X		X			X	X			X				X				X	X				
<i>Le et al</i>	Design by Feature				X	X				X	X			X							X	X		X		
<i>Huang et al.</i>	Decomposition			X		X				X	X			X							X	X		X		
<i>Sadaiah et al</i>	Feature			X		X				X	X	X		X							X	X		X		
<i>Arivazhagan, et al</i>	MVI			X		X				X	X			X			X				X	X		X		
<i>Tseng & Joshi</i>	Precedence			X		X				X	X			X							X	X		X		
<i>Prabhakar & Henderson</i>	Neural Network			X		X				X	X			X			X				X	X		X		
<i>Ding & Yue</i>	ANN			X		X				X	X			X							X	X		X		

3.4 Combination or Hybrid Approaches

Hybrid methods are based on combination of Geometry, Feature and API based methods to meet the challenges encountered in recognizing interacting features from a CAD model. Marefat et al [21-23, 63] introduced a different hint-based approach, significantly extending the classical graph-based approach to include uncertainty reasoning to avoid the computational complexity that results from sub-graph isomorphism. In addition to face Ids, the graph nodes contain information about their relative orientation and edges represented as links contain concavity information. The cavity graphs of the part are extracted and partitioned for, sub-graphs to be compared with existing feature templates for isomorphism. If the sub-graphs cannot be verified, they are further analyzed for evidence by adding “virtual links”. The Dempster-Shafer theory is utilized for uncertainty reasoning to provide the most probable virtual links. Gao & Shah [36] used a Minimal Condition Sub-graph (MCSG) for their reasoning. This is achieved by extending the classical attributed adjacency graph (AAG) to create the Extended AAG (EAAG) in which both the faces (nodes) and edges (links) carry extra information. Face attributes such as whether they belong to the stock or part, are Unifiable or not, are part of the convex hull or not, how many loops they have and their geometry like vertices and faces are used as inputs. Edge attributes such straight or curved, be part of the inner or outer loop of a face, smooth or sharp, in addition to being convex or concave, and real or virtual are taken into consideration.

Manufacturing Face Adjacency Graphs (MFAGs) are readily recognized by eliminating stock and convex hull faces. Partial patterns are called MCSGs and are treated as hints that need to be completed via addition of virtual links. Reasoning for virtual links is done by dividing feature interactions into six types, thus making it possible to generate multiple interpretations by completing the graphs in alternative ways. Another method that modified the AAG technique using hint based reasoning was introduced by Ibrahim and McCormack [64, 65]. Similar to Gao & Shah [36] approach, this technique increased the attributes of both edges and faces; however the resulting AAG, called a Modified Attributed Adjacency Graph (MAAG), was not broken down into sub-graphs. Instead, features are grouped into “families” according to hints generated by “part surfaces“, which must be in constant contact with the tip of the cutting tool which machine them. Seeking out faces with at least one concave edge

identifies part surfaces. For each such face adjacent faces with convex edges are retrieved, thus creating an opening for that face. Special cases include through features, with no part surface, and protrusions with associated surrounding part surfaces. New feature taxonomy is created based on hints from the MAAG classifying features such as simple depressions, protrusions, passages and multi-part surfaces. This work is further explained by Ibrahim and McCormack [64, 65], and comes closest to hint-based reasoning among the approaches mentioned in this subsection.

A hybrid method based using feature hints, graph theory and artificial neural network was proposed by Li, Ong & Nee [66]. Modified AAG and API were used by Zhang et al. [67]. Volume subtraction and face adjacency graph method was proposed by Rameshbabu & Shunmugam [68, 69]. Hint based and Rule based systems are utilized by Dimov et al. [70] for feature recognition. Pal & Kumar [71] used feature algebra by Karinithi [72] combined with heuristic rules to identify features. Each hybrid approach has proven to be effective in recognizing interacting feature due their robustness and strong learning capability. Each approach is effective in certain subtask of the interacting feature recognition process with optimum efficiency; however satisfactory results cannot be achieved using a single method. Extracting a complete set of machining features and their details were still not achieved.

Most systems use low-level features that are predefined in the CAD system's libraries. But higher-level features are more convenient to express the parts, domain specific functionality and machining characteristics. In a hybrid approach, it is assumed that all machining features can be machined in a single machine centre. Most components require multiple machining centres [47] to achieve intricate machining details. In most cases the subsequent machining details such as machine tool selection, operation selection, operation sequencing and machining sequencing were not considered.

Table 3.4: Combination or Hybrid Approaches

Authors	Feature Recognition Method	Category	Full Set of Machining Features Identified	3D features	2.5D /2D features	Partial Set of Machining Features Identified	Identification of Intersecting features	Compound / Array Features	Automatic Feature Recognition	Primary Factor for feature recognition		Tool Approach Direction (TAD)	Feature created by Design		Dimensional Details of Machining Feature	Adequacy Check of machining feature for manufacturing	Integration with CAPP	Integration with CAM	Standard of Exchange STEP-224	Heuristics Algorithm	Implemented Method	DETECTION OF AVAILABLE MACHINING tools	Stand alone Program/Software	Integration with CAD System	Representation of features	
										Surface	Edges		Destruction	Synthesis												
<i>Gao & Shah</i>	MCSG	Hybrid		X		X			X	X	X		X							X	X		X			
<i>Ibrahim & McCormack</i>	MAAG			X		X	X		X	X			X								X	X			X	
<i>Li, Ong & Nee</i>				X		X	X	X	X				X								X	X		X		
<i>Zhang et al</i>				X		X	X	X	X				X								X	X		X		
<i>Rameshbabu & Shunmugam</i>	Hybrid			X		X	X		X	X		X	X				X	X	X		X	X		X		
<i>Dimov et al</i>				X		X			X	X			X								X	X		X		
<i>Pal & Kumar</i>				X		X			X	X	X	X	X								X	X		X		

A summary of all the feature recognition approaches with their major merits and demerits with respect to machining capability are given summarized on each section. A substantial knowledge has been generated in this area. The major hurdle however with all these recognition techniques is that they do not consider a complete set. In addition the intersecting features have not been given adequate consideration. These are the missing links in total integration of CAD to CAPP and CAM.

International Standard Organisation developed ISO 10303-224 for describing machining features as included in Appendix I, which primarily focused towards defining machining features with intrinsic details. However the details covered are too extensive for the purpose of identifying a matching machine tool.

Adequacy of machining features was first established by Chitroda & Sivaloganathan [73], using the machining feature set provided by the Expert Machinist module of Pro/Engineer. Expert Machinist is a feature based machining (milling) software bolted on to the Pro/Engineer (CAD software) to simulate and create downwards activities in milling application. Chitroda & Sivaloganathan considered fifty different machining components and established that the machining feature set provided by Expert Machinist is adequate to define any machining job. Srikskumar [74] had used feature mapping technique for identifying manufacturability of components using expert machinist feature set which can be used as early as design stage [75]. However PTC has withdrawn Expert Machinist thus forcing the development of an adequate feature set. Adequacy of the new Machining Feature set would be automatically established if the new set can replicate the features provided by Expert Machinist. Such a new set of machining features is proposed in this thesis and is described in the following section.

3.5 Surfaces and Surface Parameters Characterising Machining Features

Machining features are characterised by surfaces and each surface has its own parameters. Machining features and their constitutive surfaces are discussed below.

3.5.1 Step Feature

Step features is created by two plane surfaces from the workpiece S1 and S2 as shown in Figure 3.7, both the surfaces continuously join together to form a V between them, the step features parameters can be identified from the surfaces.

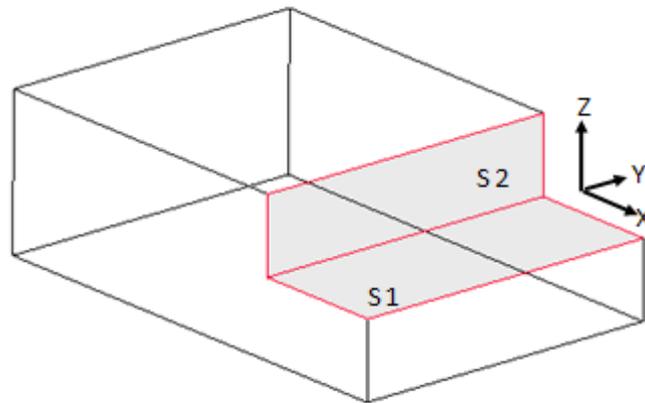


Figure 3.7: Step Feature

Orientation of the features depends on normal vector of the bottom surface S1, length and width are identified from surface extremes. Depth of the step feature is identified using the plane surface S2 and its surface extremes. Figure 3.8 illustrates the two surfaces that create the step feature.

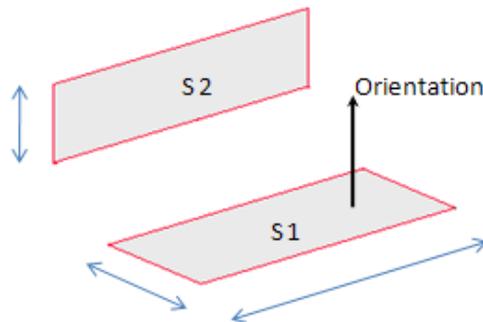


Figure 3.8: Surface Creating the Step Feature

3.5.2 Slot Feature

Slot Feature consists of three surfaces, S1, S2 and S3 from the workpiece of which two surfaces S2, S3 continuously joined with S1. Depending on the surface a) if S1 and S2 can be parallel or inclined to each other as shown in Figure 3.9(a) is called as through slot and b) S1 and S2 are connected continuously to each other also as shown in Figure 3.9(b) is called as open slot.

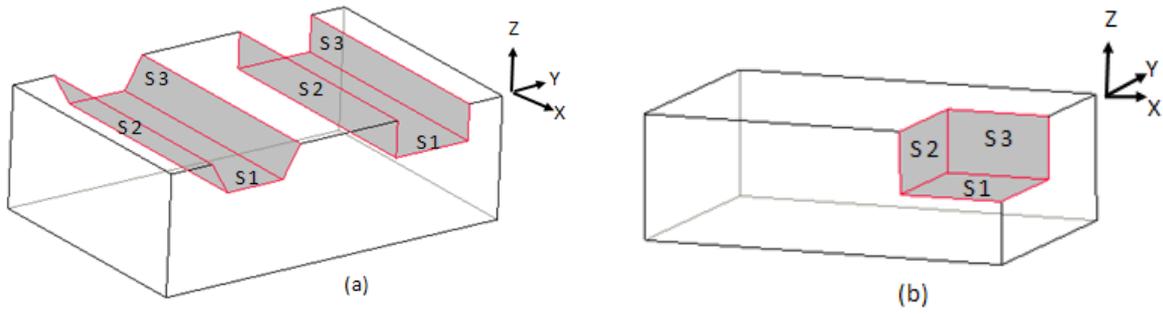


Figure 3.9: Slot Feature

Parameter of the slot features can be identified from the surfaces S1, S2 and S3, orientation of the slot depends on the bottom surface S1, length, width can also be identified from the plane surface S1's surface extremes. The depth of the slot feature is identified from the plane surface S2 or S3 from its surface extremes. Various parameters of the slot feature and the three surfaces creating the slot feature is illustrated in Figure 3.10.

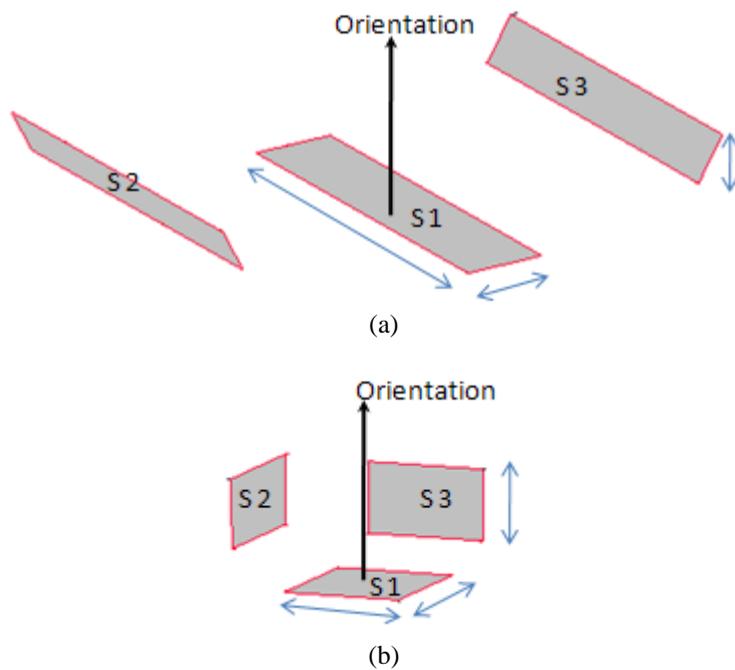


Figure 3.10: Parameters of a Slot Feature

3.5.3 Round Feature

Round Feature consist of single cylindrical surface S1 as shown in Figure 3.11.

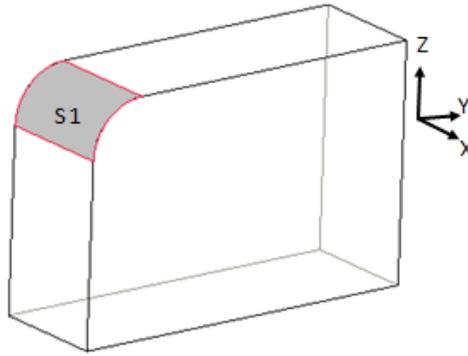


Figure 3.11: Round Feature

Parameters of the round feature such as its orientation, dimensions are identified from the cylindrical surface S1 and its surface extremes as shown in Figure 3.12.

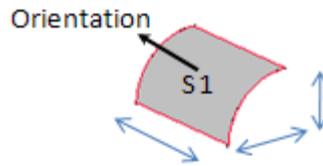


Figure 3.12: Parameters of Round Feature

3.5.4 Planar Feature

Planar feature is made up of a single plane surface S1 from the workpiece as shown in Figure 3.13(a), some time the surface might consist of contour or island called as boss as illustrated in Figure 3.13(b).

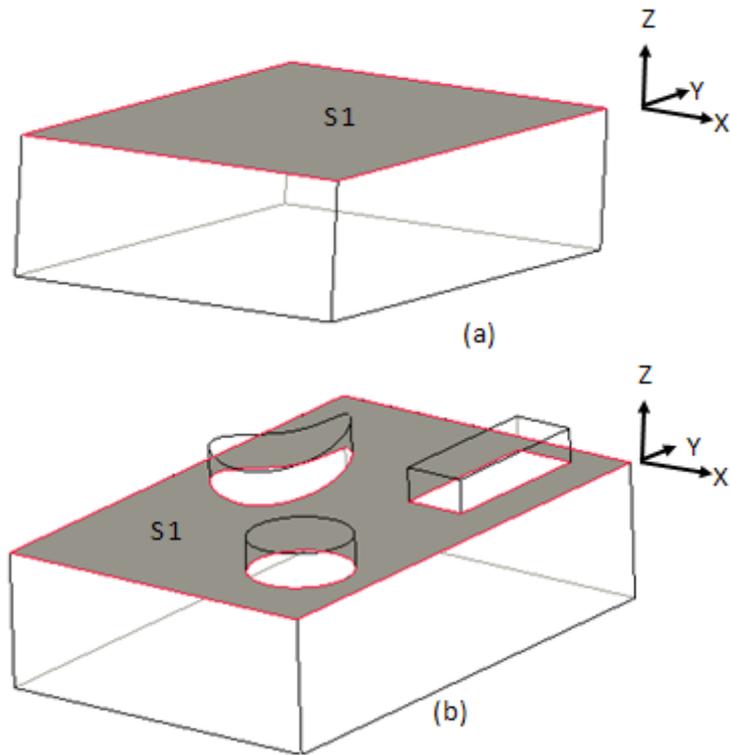


Figure 3.13: Planar Feature

Parameters of the planar feature such as its orientation, dimensions are identified from the plane surface and its surface extremes as shown in Figure 3.14.

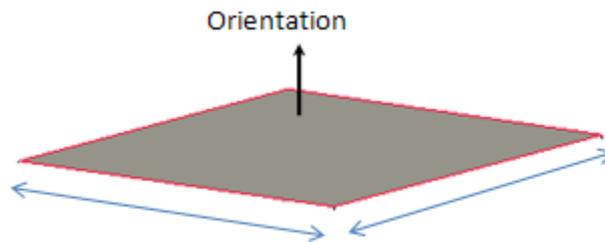


Figure 3.14: Parameters of Planar Feature

3.5.5 Chamfer Feature

Chamfer feature is made up of a single plane surface S1 from the workpiece as shown in Figure 3.15.

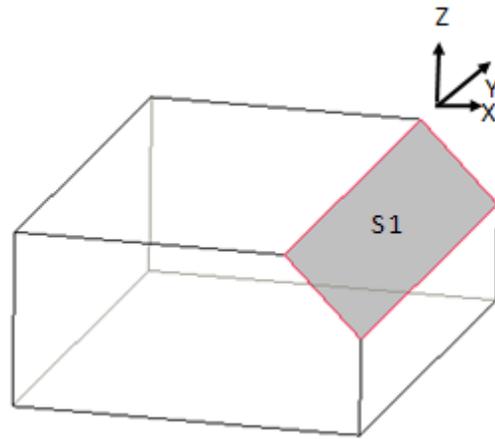


Figure 3.15: Chamfer Feature

Parameter of a chamfer feature such as its orientation, dimensions are identified from the plane surface S1 and its surface extremes as shown in Figure 3.16.

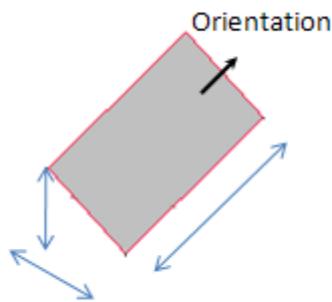


Figure 3.16: Parameter of Chamfer Feature

3.5.6 Hole Feature

Hole features is made up of two cylindrical surface called as through hole, or two cylindrical and one plane surface blind hole from the workpiece. Figure 3.17 illustrates different kinds of holes, a) if the cylindrical surfaces are parallel to each other they are straight hole and b) if the cylindrical surfaces are inclined they are conical holes.

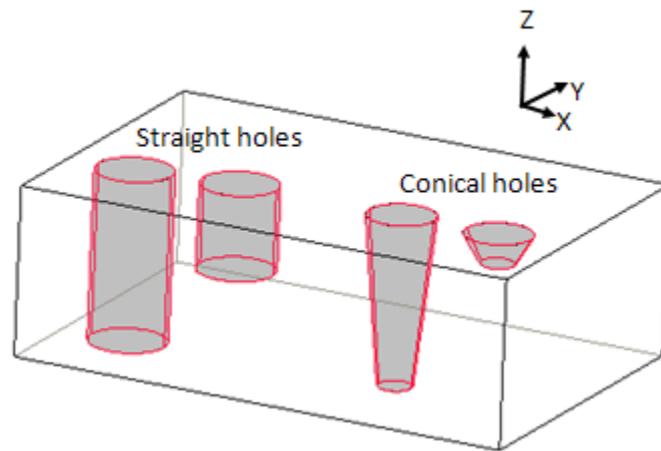


Figure 3.17: Hole Features

Parameters of a hole feature such as its orientation, dimensions are identified from the plane surface in absence the cylindrical surface is used and its surface hole features surface extremes are shown in Figure 3.18.

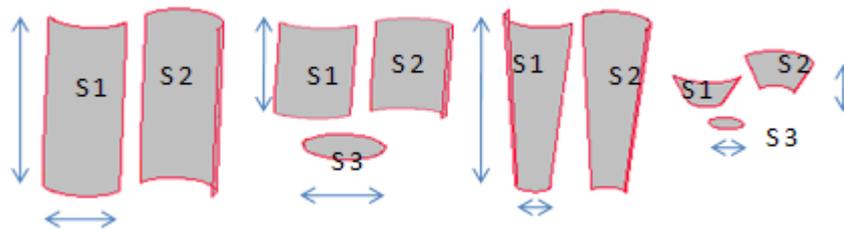
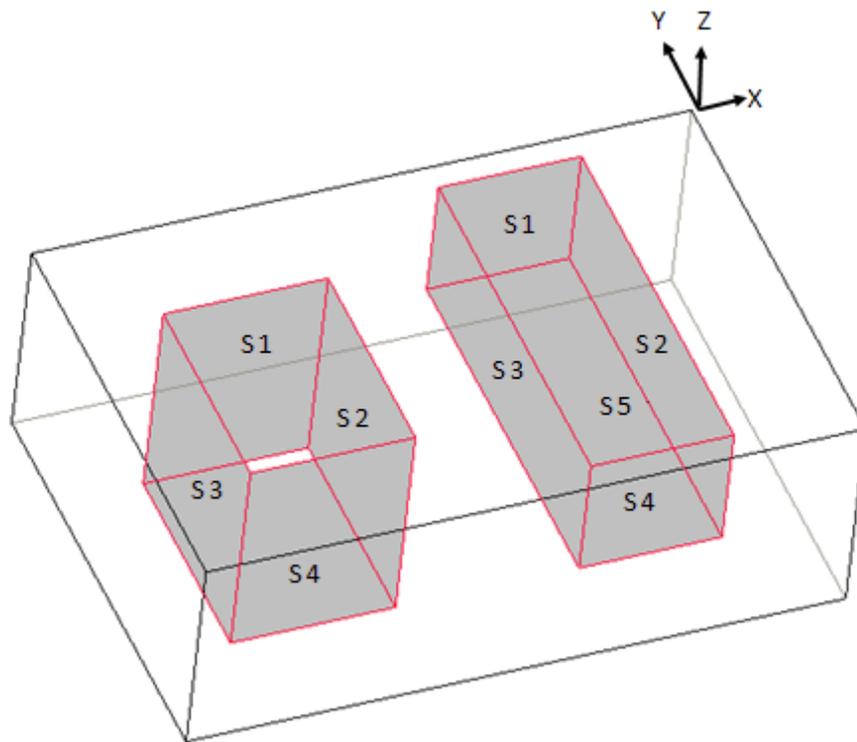


Figure 3.18: Parameter of Hole Feature

3.5.7 Pocket Feature

Pocket features is of three types a) through pocket which consist of four plane surfaces from the workpiece of which pair of surfaces are parallel to each other, b) five plane surface of which two sets are parallel to each other and these are connected to the fifth surface as shown in Figure 3.19(a) and c) b) four plane surfaces from the workpiece of which two planes are parallel and other two are perpendicular to each other as shown in Figure 3.19(b).



(a)



(b)

Figure 3.19: Pocket Feature

Parameter of the pocket features can be identified from the surfaces S1, S2, S3 and S4, orientation of the slot depends on the bottom surface S5 in absence its identified from the S1 or S2 surface, length, width can also be identified from the plane surface S5's surface extremes. The depth of the slot feature is identified from the plane surface S1 or S2 from its surface extremes. Various parameters of the pocket feature and the plane surfaces creating the slot feature is illustrated in Figure 3.20.

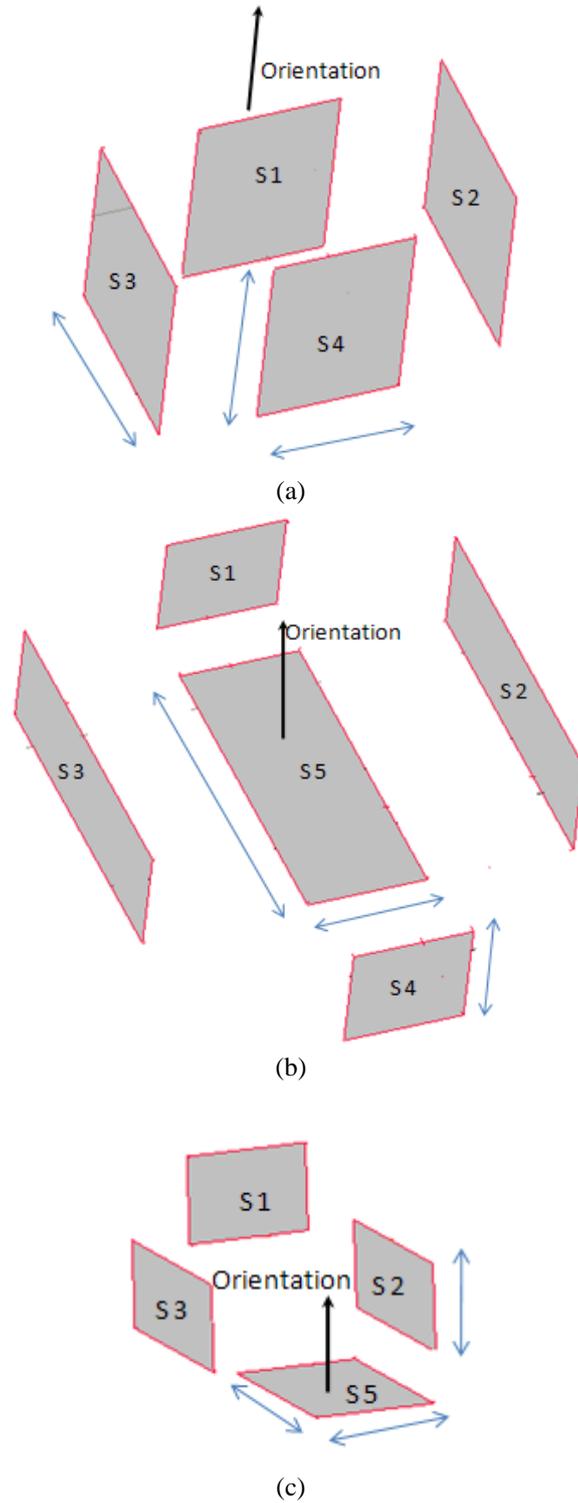


Figure 3.20: Parameters of a Pocket Feature

This section thus highlights the geometric properties that are needed to analyse any manufacturing feature. A lot of research work has been done [15], [17], [21], [27] on feature definition and recognition methods, but their adequacy has never been checked. Chitroda and

Sivaloganathan [73]. have established that Expert Machinist features are adequate for describing all machining operations performed in a Vertical Machining Centre. But Pro/Engineer does not permit access to these machining feature parameters. A machining feature set whose parameters are accessible was needed to achieve the objectives of the research. Since the feature set provided by Expert Machinist was proven to be adequate a set that can map all features in Expert Machinist has been developed. It is created to make bolt-on to Pro/Engineer. Section 3.7 describes them.

3.6 Cuts as Machining Features and their Characteristic Surfaces and Parameters

The high level modelling entities of feature-based design can provide the necessary information needed by applications to store and retrieve information of a particular feature. Geometry issues depend on the feature creation methods supported by the modeller. The classification of design features may vary for different solid modellers. Various design features available in Pro/Engineer are;

- Protrusion
- Cut
- Chamfer
- Hole
- Round
- Rib
- Shell
- Pipe

The primary feature creation methods in part modelling are protrusions (mass additions) and cuts (mass removal). Protrusions and cuts are created using 2-D cross sections that are extruded, revolved, swept or blended in creating the required shapes. As machining is the process of material removal, so a base is created as a protrusion considering as raw stock and further cuts are added on to raw stock. The various cuts creating the machining features are described below;

3.6.1 Step Feature

The Figure 3.21 illustrates the creation of a step feature using the design feature cut in Pro/Engineer. 2D sketch is drawn as highlight in red colour such that the corner of the drawing

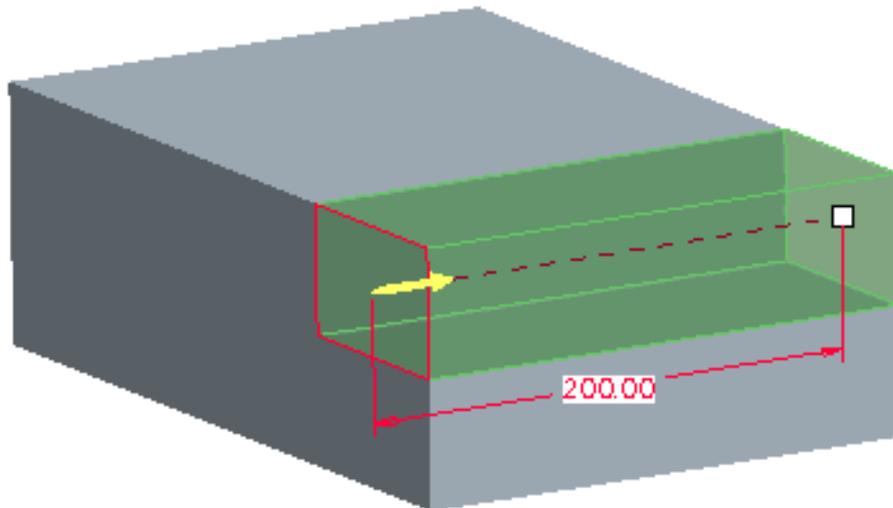
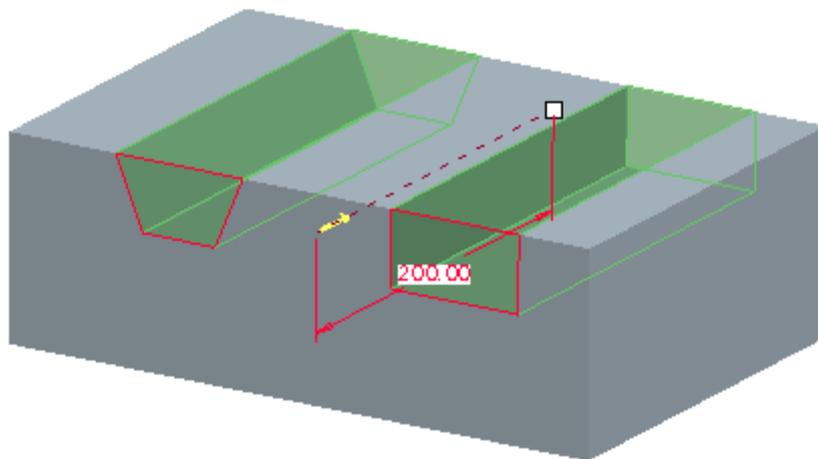


Figure 3.21: Step Feature

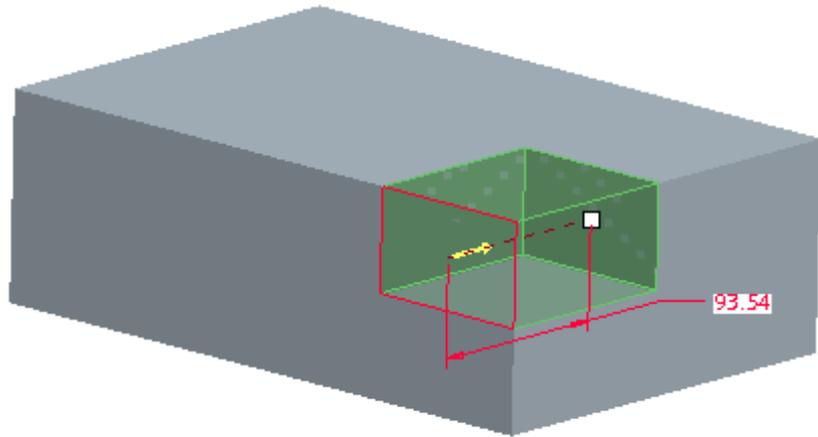
coincides with that of the workpiece. The sketch is then swept across in the direction of the arrow to create the cut to the full length, the material removed as this process is highlighted in green. The material removed would create two plane surfaces which would form a V shape between them to form the step feature

3.6.2 Slot Feature

The Figure 3.22 illustrates the creation of a slot feature using the design feature cut in Pro/Engineer.



(a)



(b)

Figure 3.22: Slot Features

2D sketch is drawn as highlight in red colour such that the top end of the drawing coincides with that of the workpiece. The sketch is then swept across in the direction of the arrow to create the cut to the full length for through slot as shown in Figure 3.22(a). Open slot is created with a 2D sketch that coincided to the corner of the workpiece and swept to a limited distance and not throughout as shown in Figure 3.22(b). Outcome of the design process would result in material removed as highlighted in green. The material removed would create three plane surfaces which would form the slot feature.

3.6.3 Round Feature

The Figure 3.23 illustrates the creation of a round feature using the design feature round in Pro/Engineer. The edge on which the round has to be created is selected as highlight in red colour, and the radius for rounding is designated. The outcome of the design process in Pro/Engineer will result in removal material from the base to create a single cylindrical surface on the edge selected as shown in Figure 3.23.

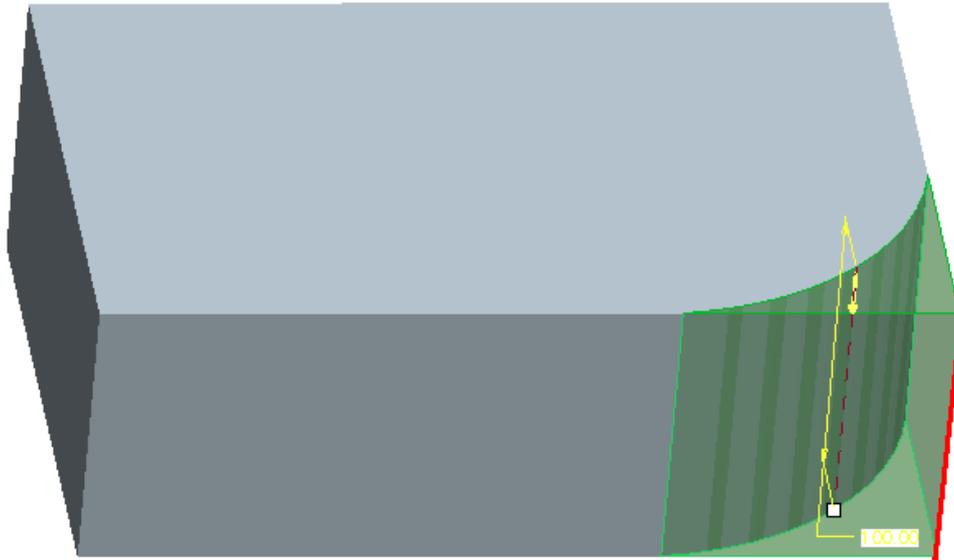
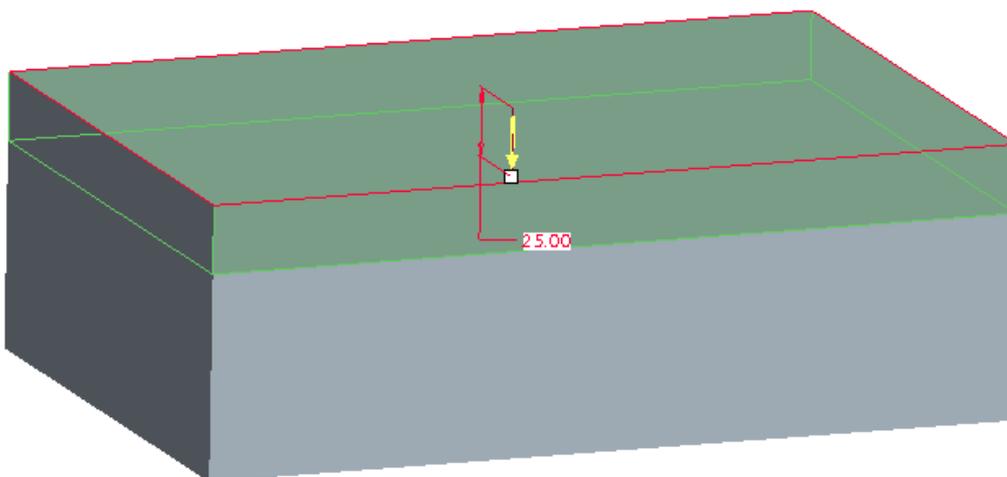


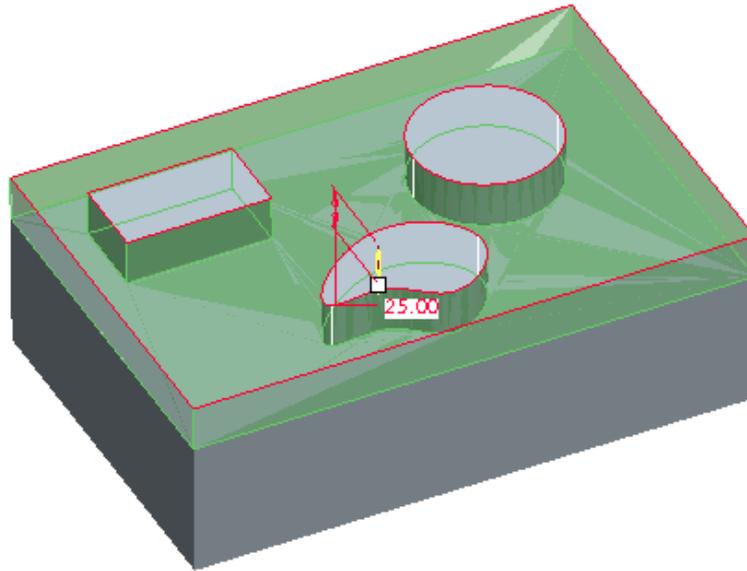
Figure 3.23: Round Feature

3.6.4 Planar Feature

The Figure 3.24 illustrates the creation of a planar feature using the design feature cut in Pro/Engineer. 2D sketch is drawn as highlight in red colour such that the outline of the workpiece coincides with that of the drawing. The sketch is then swept across in the direction of the arrow and swept to a limited distance and not throughout as shown in Figure 3.24(a). Creation of a small island of material within the process creates the bosses as shown in Figure 3.24(b) Material removed as this process is highlighted in green. The material removed would create single plane surface which would form the planar feature.



(a)



(b)

Figure 3.24: Planar Feature

3.6.5 Chamfer

The Figure 3.25 illustrates the creation of a Chamfer feature using the design feature chamfer in Pro/Engineer. The edge on which the chamfer has to be created is selected as highlight in red colour, and the angle and length of the chamfer is designated. The outcome of the design process in Pro/Engineer will result in removal material from the base to create a single plane surface on the edge selected as shown in Figure 3.25.

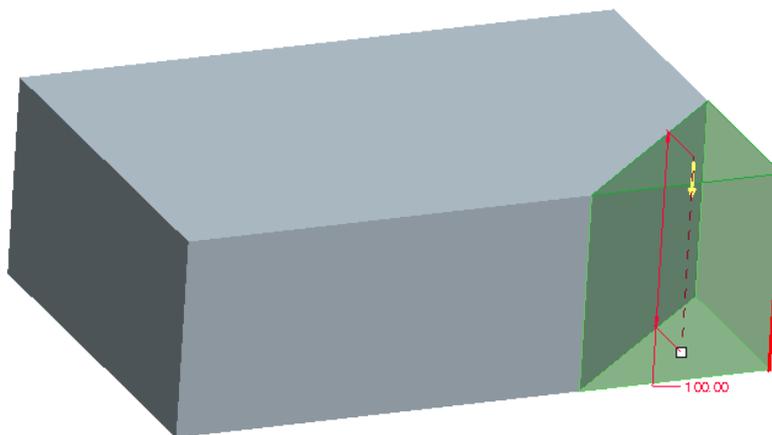


Figure 3.25: Chamfer Feature

3.6.6 Hole

The Figure 3.26 illustrates the creation of a Chamfer feature using the design feature hole in Pro/Engineer. The surface on which the hole has to be created is selected and referenced, the hole diameter is designated if its straight hole as shown in Figure 3.26 or a conical hole is sketched. The outcome of the design process in Pro/Engineer will result in removal of material from the base to create a two cylindrical surface for through hole and a two cylindrical and a plane surface for a blind hole.

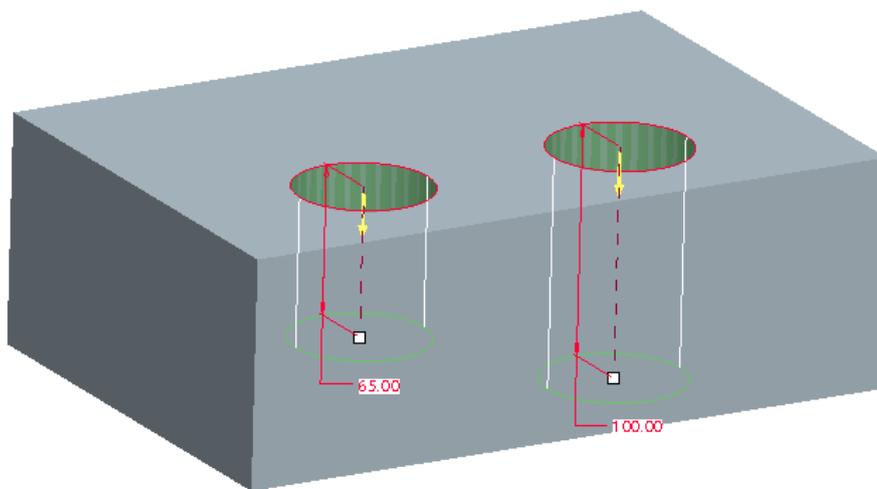
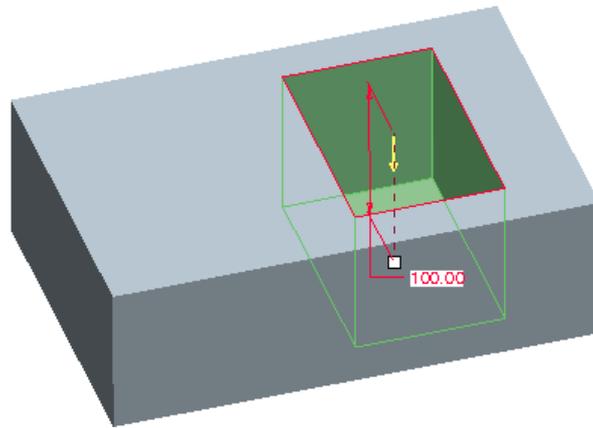


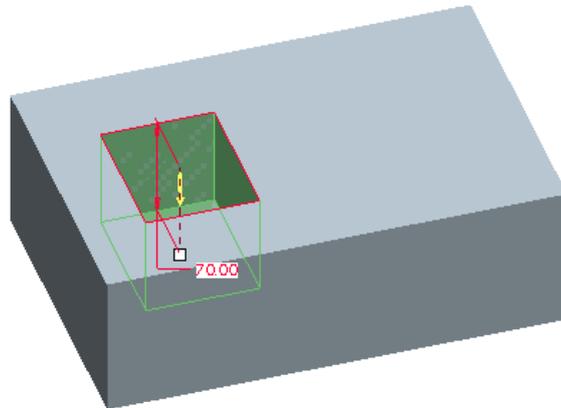
Figure 3.26: Hole Feature

3.6.7 Pocket

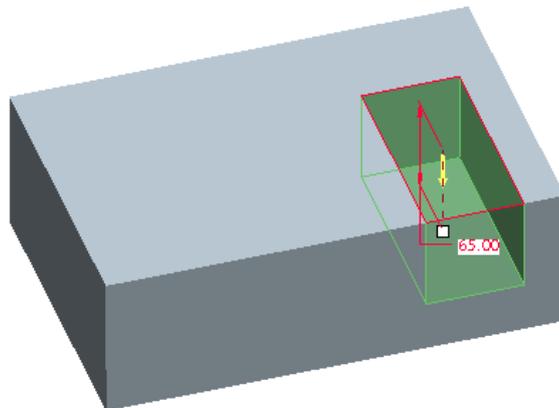
The Figure 3.27 illustrates the creation of pocket feature using the design feature cut in Pro/Engineer. 2D sketch is drawn as highlight in red colour such that the sketch is within the workpiece. The sketch is then swept across in the direction of the arrow to create the cut to the full length for through pocket as shown in Figure 3.27(a) and blind pocket is created with limited distance as shown in Figure 3.27(b). Open pocket is created with a 2D sketch that coincided to the edge of the workpiece and swept to a limited distance and not throughout as shown in Figure 3.27(c). Outcome of the design process would result in material removed as highlighted in green. The material removed would create a) four plane surfaces for open and through pocket and b) five plane surfaces for a blind pocket.



(a)



(b)



(c)

Figure 3.27: Slot Feature

3.7 Chapter Summary

The survey on Machining has been carried out to understand Machining Process and the modelling approach (Machining Feature approach) taken to model them. The following can be said as the summary of the survey.

- There exists a class of components which can be classified as high value added components and they are more suited for CAD/CAM software based coding for the generation of their NC code.
- Analysis of the machining of some typical components led to the understanding of the need and opportunity for Machining Feature based approach.
- Survey showed the two major sets of Machining Features, one developed by ISO and one developed by Expert Machinist.
- Since machining process is about producing surfaces, surface parameters for the production of these features have been studied.
- A cut-based feature set has been developed to model machining.

Chapter 4: Methodology

4.0 Introduction

The broad aim of this research work was to develop a systematic methodology to choose a machine tool, by matching feature complexity of machining job presented to that of machine tool. This involved the integration of two main groups of considerations (a) the machine tool and its capabilities and (b) the required component and the raw stock.

Survey of literature reveals that an Alphanumeric Code can be adequately employed to represent a machining centre and machining features can be employed to represent a machining job. The work started with the machining features provided by Expert Machinist but after its withdrawal a new set similar to it was needed. A new set mimicking the features provided by Expert Machinist has been developed.

The methodology adopted here can be summarised as “*generate an alphanumeric code for a given machining job and draw matching machine tools using this code from a database of machine tools which uses similar alphanumeric codes as the sorting field. A choice can then be made by the user for a particular machine tool.*” The methodology adopted to carry out this work is shown as a flow chart in Figure 4.1

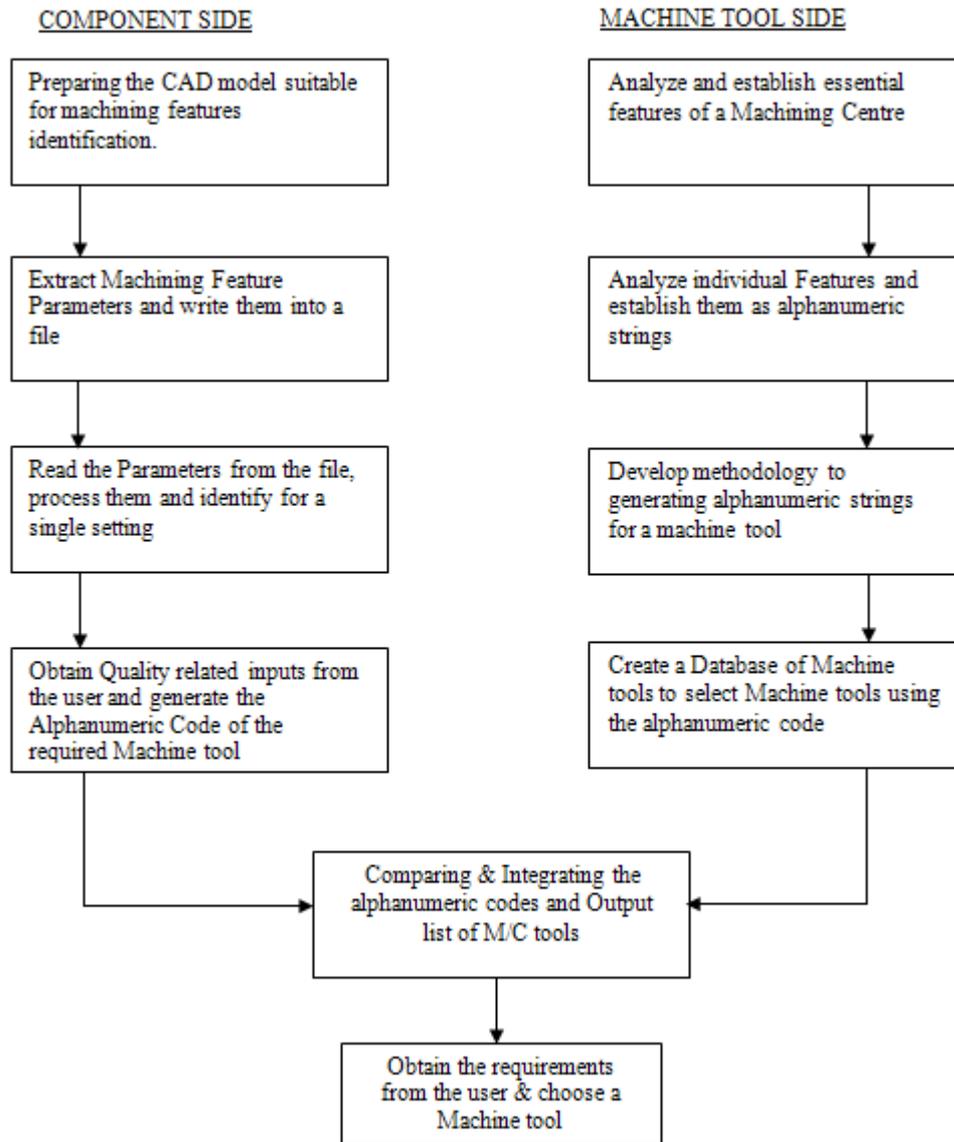


Figure 4.1: Flow Chart Showing the Methodology

The left hand side of the flow chart outlines considerations from the component and its raw stock, to generate an alphanumeric code of the component to be machined with the required accuracy. The right hand side of the flow chart demonstrates the processing of the information about Machine Tools and stores them in a database. The data can be browsed and selected using the alphanumeric code of the component. The alphanumeric code thus acts as the link between the two groups of information. Once a list of suitable machine tools is established the user can choose the machine tool that he prefers. The following subsections explain the activities carried out in each of the arm in the methodology outlined in the flow chart.

4.1 Analyze and establish essential features of a Machining Centre

4.1.1 Background

BS4656-30 defines a Machining Centre as a numerically controlled machine tool capable of performing a variety of operations at one set-up of a workpiece (normally two or more of turning, boring, drilling, milling and screwing and threading) and able to select and change tools, position the workpiece and the cutter, and control speeds and feeds and ancillary services (e.g. coolant flow).

BS4656-30 [76] outlines combinations of axes configurations that are possible and they are given in Appendix H. Research work by *Vragov, Protman, Davydov, Voronov and Ito* on Structure and Coding of NC Machine Configurations have proceeded along developing codes showing the motion of load carrying system. The question however is, what are the details that have to be provided by the code. Research publications did not help much. Sales brochures produced by machine tool manufacturers are the prime sources of information for precision engineering companies to base their choice of machine tools. Therefore the information provided in the sale brochures should be sufficient to make the choice. An analysis of the sales brochures was chosen as the method to identify the features to be included in the code. Section 4.1.2 describes the work carried out.

4.1.2 Analysis of Information about Machine Tools in the Market

Sales brochures provided by machine tool manufacturers are aimed at potential users and they provide vital information, which in the opinion of the company are the factors that would sway the decision towards the purchase of the machine. For example consider the information provided by DUGARD machine tools about their Vertical Machining Centre 660 in Appendix G. The information given includes basic details consisting of the traverse motions, number of tool and tool changer, spindle speed and the type of controller. Further information regarding options of spindle, machine structure, capacity, weight and lubrication are given in the next section of the broacher. This enables user to get a closer understanding that the machine tool can offer for machining. Finally any additional features which are optional on the machine tool are provided for the user to add on to existing model of machine tool, if required. Machine tool brochures by Haas gives further details about their rigid body structure, motion controls, spindle features, coolant, chip removal, and other conveniences

like Dust removal and M-Functions individually. The brochures also consist of details and the differences between their own models to differentiate as a matrix so the user can identify the required feature that might be present with the model of interest.

Sale brochures from manufacturers for thirty nine machine tools of different sophistication were analyzed and the summarised analysis is given in Table 4.1. The columns indicate the information element and the rows indicate the machine tool models considered.

Table 4.1 Machine Tool Analysis (Continued)

Machine tool Model	X Traverse	Y Traverse	Z Traverse	a rotation	b rotation	c rotation	Wk Tab Load Capacity	T Slots on Work Table	Chuck on Work Table	Rapid Traverse	Accuracy	Repeatability	Auto. Tool Changer	Tool Magazine	Auto. Pallet Changer	Controller	USB/ Ethernet/ HD Interface	Off line control	Expandable memory	Spindle Speed	Spindle feed	S.tap BT/CAT/HK/SHK	Two Speed Gear box	Coolant System	Thr. Spdle Coolant	Coolant filter	Swarf Removal	Dust Extraction System	Guard	Electronic hand wheel	Tool and Part Probing	Additional M Functions	Machine Weight
Dugard Eagle 660	☺	☺	☺	☹			☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☹		☺	☺			☺	
Dugard Eagle 450XP+	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺			☺	☺	☺	☺						☺	☺			☺	
Dugard Eagle 850	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☺		☺	☺			☺	
Durgard Eagle X5	☺	☺	☺	☺		☺	☺	☺		☺	☺	☺	☺	☺		☺			☺	☺	☺	☺	☺			☺		☺	☺		☺	☺	
Hardinge VMC XR series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☺		☺	☺			☺	
Hardinge VMC 500AX	☺	☺	☺	☺		☺	☺	☺		☺	☺	☺	☺	☺		☺			☺	☺	☺	☺				☺		☺	☺		☺	☺	
Hardinge XR APC	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☺		☺	☺			☺	
Hardinge XR HPC	☺	☺	☺		☺		☺		☺	☺	☺	☺	☺	☺		☺				☺	☺	☺				☺		☺	☺			☺	
Hardinge XV series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☺		☺	☺			☺	
Hurco VM series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺						☺	☺			☺	
Hurco VMX series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☺		☺	☺			☺	
Hurco VTXU	☺	☺	☺	☺		☺	☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺	☺			☺		☺	☺		☹	☺	
Hurco VTXV	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☺		☺	☺		☹	☺	
Hurco HTX	☺	☺	☺		☺		☺	☺		☺	☺	☺	☺	☺	☺	☺				☺	☺	☺	☺			☺		☺	☺		☹	☺	
Mazak FH series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺	☺	☺				☺	☺	☺						☺	☺			☺	
Mazak FJV series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺		☺				☺	☺	☺				☹		☺	☺			☺	
Mazak HCN series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺	☺	☺				☺	☺	☺						☺	☺			☺	
Mazak VCN series	☺	☺	☺				☺	☺		☺	☺	☺	☺	☺	☺	☺				☺	☺	☺						☺	☺			☺	
Required Features	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺				☺		☺			☺	☺							

4.1.3 Choice of Information Needed to be Incorporated into the Code

Preceding analyses identify the important features that need to be considered for selection of a machine tool by an end user i.e. the precision engineer. However all these features are not needed for an outsourcer for example number of T slots. The identified features are (a) traverse and rotary motions (b) automation, (c) cutting tool, (d) spindle performance (e) fixtures (f) accuracy (g) repeatability (h) Controllers and (i) presence of cooling system, dust & swarf removal system are only considered.

Traverse and *Rotary* motions are two major type of motion that can be carried out by the machine tool, which would be used for setting and forming of the component.

Automation would represent the speed at which the component can be loaded using APC and cutting tool can be changed using ATC to reduce time of machining.

Number of *cutting tool* is necessary for a high value added component when the machining might require more than one cutting tool to reduce the number of setup.

Spindle performance like there speed and feed are necessary for removing material, depending on the component.

Fixture: Components are needed to be held in proper orientation using *fixture* for the cutting tool to approach the component for machining.

Accuracy and *repeatability* depend on the slide-ways and the motor which enable the traverse and rotary motions to be executed with minimum error.

Controllers: Motions and cutting parameters are managed by *controllers*

Other Functions: to aid the machining process *cooling*, *dust* and *swarf* removal system are needed.

4.2 Analyzing Individual Features and Establish them as Alphanumeric Strings

Each of the machining feature identified in section 4.1.4 are essential for a precision engineer to select appropriate machine tool for a job. The representation of these features as alphanumeric strings is discussed in this section.

Traverse and *Rotary* motions would define the axis of freedom for the machine tool. Each motion can be represented using the nomenclature of right hand coordinate system of machine tool and non moving block as “0”, which is followed by the actual rectilinear motion in millimetres and possible angle for rotary motion. Right Hand Coordinate system uses X, Y, Z & U, V, W for major and auxiliary traverse axes and a, b, c & i, j, k for major and auxiliary rotary axis respectively. The Table 4.2 represents the alphanumeric string to represent the traverse and rotary motion.

Table 4.2: Axis

Traverse			Rotary			
	Axis	Motion in mm	Alphanumeric String	Axis	Angle of Rotation	Alphanumeric String
Major	X	0500	X500	a	30	a30
	Y	0600	Y600	b	60	b60
	Z	1000	Z1000	c	120	c120
Auxiliary	U	300	U200	i	15	i15
	V	250	V250	j	45	j45
	W	100	W100	k	85	k85

Automation: Automatic Tool Changer (ATC) and Automatic Pallet Changer (APC) is represented as manual or auto with symbol ‘A’ for auto and ‘M’ for manual followed by T for tool and P for pallet. Number of *cutting tool* available in a machine tool magazine is represented as numeric number as which is preceded by with ATC code and number of pallet by APC code. The Alphanumeric string for the automation would consist of first character to represent type of changing system followed by tool or pallet and finally number of tool or pallet available for the changing system. The Table 4.3 represents the alpha numeric string for the automation system of tool and pallet.

Table 4.3: Automation

Automation	Changing System	Quantity	Alphanumeric String
Pallet	Manual	1	MP01
Tool	Automatic	24	AT24

Spindle performance consists of feed rate, number spindle head and spindle speed. Spindle speed is represented in revolutions per minute (rpm)/100 and feed is represented in meters per min. Representation starts with numerical value of feed rate followed by number of spindle

head these two details forms a three digit number and then followed by spindle speed both the number are separated by alphabet 'S' to denote the spindle details. The Table 4.4 represents the details of spindle and the alphanumeric string.

Table 4.4: Number of Spindles

Number of Spindles	Feed rate	Spindle Speed	Alphanumeric String
1	24	5000	Z24-S50
3	30	12500	3Z30-S125

Type of *fixture* and *Controller* is abbreviated using four places of alphabets to represent them, for example a standard type of fixture can be represented as STAN for T-slot, CHUK for chuck and controller system Siemens can be represented as SIEM. Table 4.5 shows the alphanumeric string for the fixture and Table 4.6 shows the alphanumeric string for the controllers.

Table 4.5: Fixture Type

Fixture Type	Alphanumeric String
T slot	STAN
Chuck	CHUK
Wise	WISE

Table 4.6: Controller Type

Controller Type	Alphanumeric String
Fanuc	FANU
Hiedenhain	HEID
Sinumerick	SINK

Accuracy and *repeatability* are represented using two digit numeric values. Accuracy (positional accuracy) and repeatability in microns are represented in alphanumeric string in Table 4. 7.

Table 4. 7: Accuracy & Repeatability

	Value	Alphanumeric String
Accuracy	0.003mm	03
Repeatability	0.001mm	01

Presence of *Coolant*, *Swarf* and *dust* removal system is represented with individual alphabet “P” and absence with “F”. Alphanumeric string would consist of three digit character strings which will denote the presence or absence of coolant, swarf and dust respectively, the Table 4.8 representation of the alphanumeric string of the systems presents.

Table 4.8: Coolant System

Coolant System	Swarf Removal System	Dust Removal System	Alphanumeric String
Available	Available	Absent	PPF
Available	Available	Available	PPP
Absent	Absent	Absent	FFF

4.3 Methodology to develop Alphanumeric Code for Machine tool

The alphanumeric string of each feature is clustered together to created the alphanumeric code to represent the machine tools. In addition make and model of the machine tool is included in the machine tool code with the strings. A completed code would consist of alphanumeric string starting from the

- Make and model
- Number of axis
- Repeatability,
- Accuracy
- Automation
- Spindle details
- Fixture
- Controller
- Motion blocks
- Coolant, swarf & dust removal systems.

Each of these features is separated with a colon, which would facilitate to add any future feature to be included in the code. Motions of the machine tool are represented starting from the component and ending at the cutting tool. Normal three axis Milling machine tool with single spindle would have a single line of contact from the component to cutting tool.

Machines with more than one spindle can be represented as separated loops connecting from the work piece to the spindle. Consider the Vertical Milling Machine Tool in Figure 4.3 consisting of two spindle heads, considering the looping shown in blue arrow, the loop separates after the X axis motion. The point of separation of the two loops can be represented with “+” which would enable us to represent more than one spindle. Considering the machine tool shown in Figure 4.3 its motions can be represented as $XY+0Z +0W$. Consider the machine VMC660 by Dugurad details included in Appendix G, its feature, feature values and alphanumeric string is represented in Table 4. 9: Alphanumeric Strings .

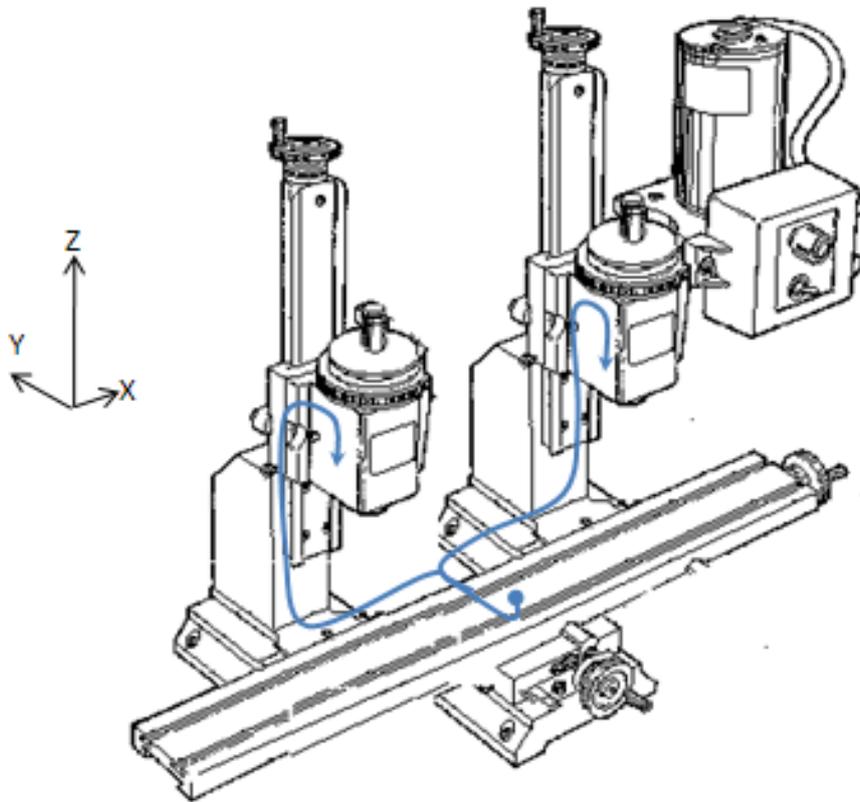


Figure 4.2: Vertical Milling Machine with Double Spindle

Table 4. 9: Alphanumeric Strings

Feature	Feature Value	Alphanumeric String
Model	Duguard660	Duguard660:
Number of Axis	3	03:
Repeatability	0.003mm	03:
Accuracy	0.004mm	03:

Automation	ATC, Manual Pallet Change	MP01: AT24:
Pallet Changer	1	
Spindle Details	30m/min, single spindle, 8000rpm	301S80:
Fixture	T-slot is available as standard	STAN
Controller	Heidenhain	HEID
Traverse X,Y,Z	660mm, 520mm, 510mm	X660:Y520:0Z510:

4.4 Creating database and selecting machine tools using alphanumeric code

Structured collections of machine tools with their details are to be created, that would consist of all the details required by the alphanumeric string and record them into database to create the alphanumeric code. A wide variety of database structures are already available which need to be modified for the requirement. The major types of data base are (a) flat file database, (b) Database management and (c) Relational. Machine tool details can be collected from various manufactures of machine tool by (a) Visits to their units, (b) industrial exhibitions (c) internet resource and (d) Brochures. Collected machine details would be tabulated extensively with machining specific details that would be required for generation of alphanumeric string. Collected machine tool details can be added into database, and the database should manageable for creating, modifying and querying the machining features. A simple application can be created where the details of the machine tool can be entered through form and using the fields from the entered values alphanumeric code can be generated.

4.5 Preparing the CAD Model Suitable for Machining Features Identification.

Machining is a process where parts of the material are removed from the raw stock to bring it to the shape of the finished component. Consider the drilling process shown in Figure 4.4. The material removed is shown in green. Depending on the type of the geometric shape created due to material removal, the shapes are classified into specific Feature class called Machining Features.

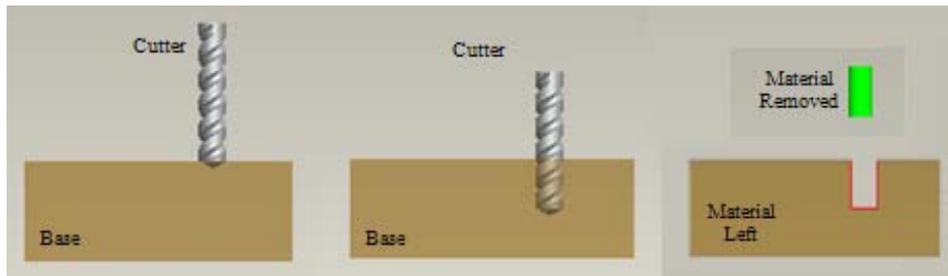


Figure 4.3: Material removal from raw stock

Figure 4.5 shows nine shapes created by material removal or in other words nine machining features. These machining features are created by effecting cuts on the raw stock.

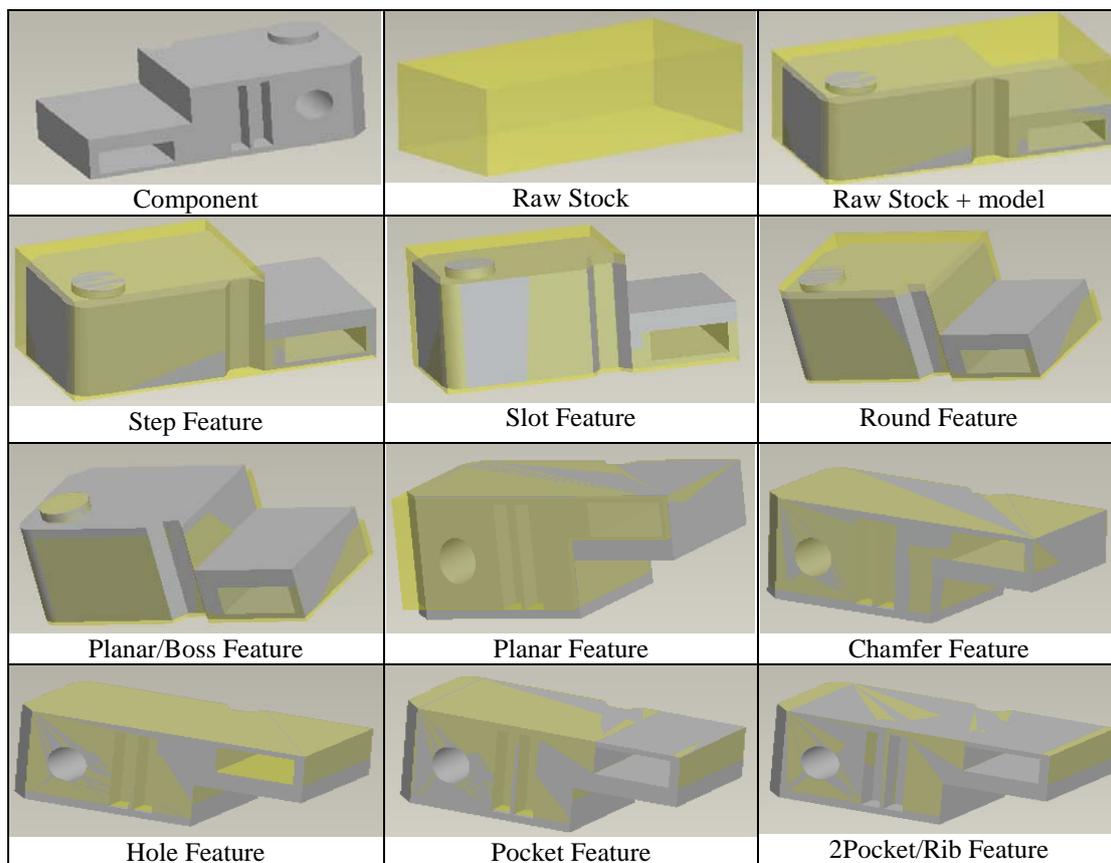
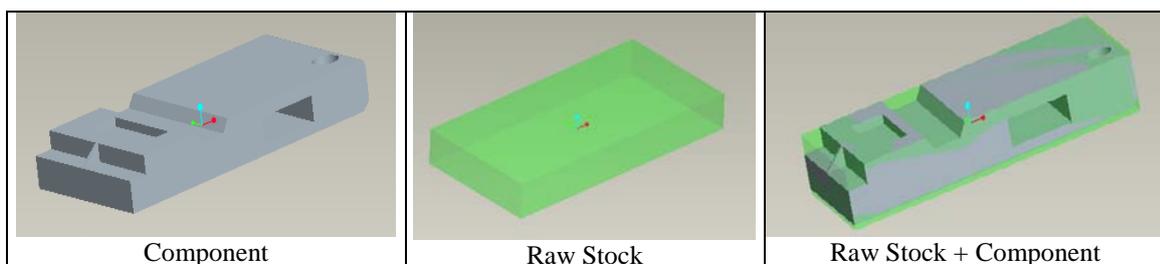


Figure 4.4: Considered Machining Feature



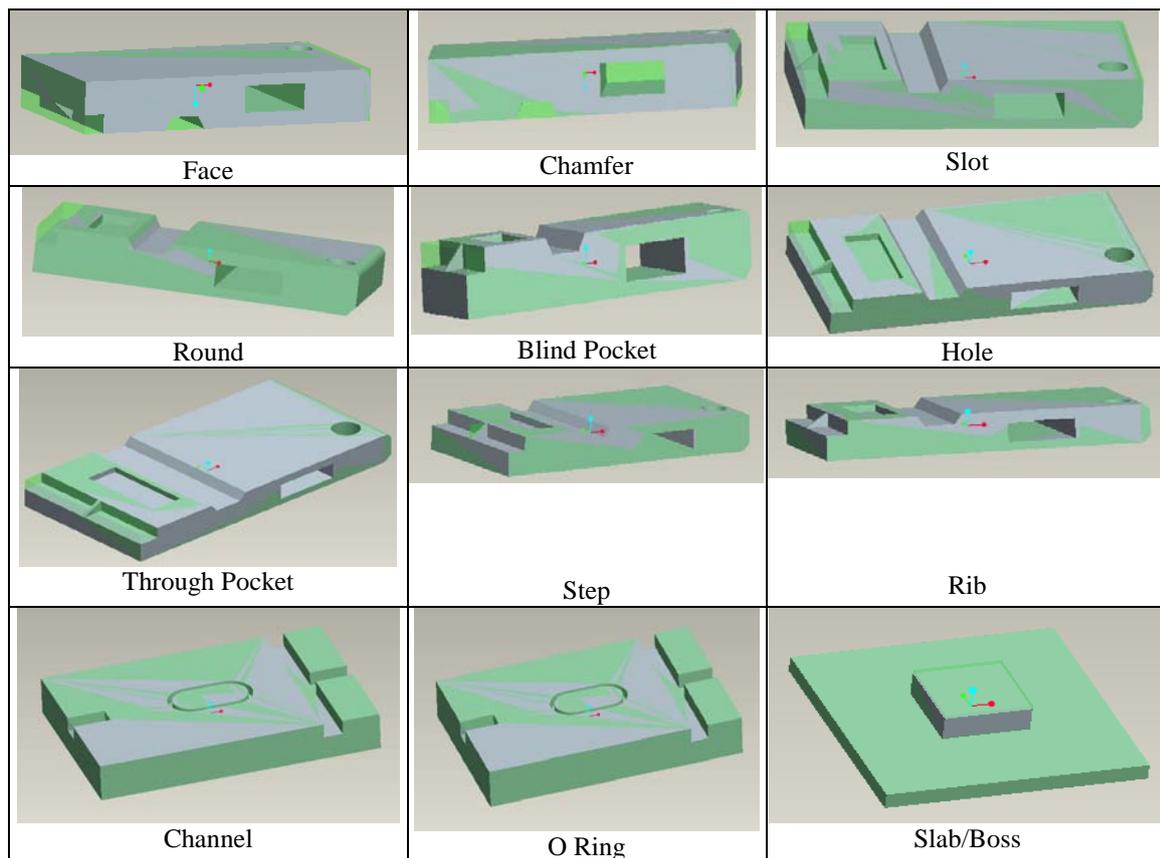


Figure 4.5: Machining Feature as described by Expert Machinist

Expert Machinist is a feature based production milling software bolted on to the Pro/Engineer software that uses machining features. The machining features as described by expert machinist are tabulated in Figure 4.6. *Citroda and Sivaloganathan [73]* have shown that the machining features defined by Expert Machinist are sufficient to define any machining job.

Most of the machining features, like face, step, pocket, hole, chamfer and round, described in Figure 4.6 are similar to that of Expert Machinist. Features like Slab and Boss are similar to that of proposed planar feature with island of material left in the middle. Other features like Rib and flange feature can be created in combination of proposed feature. O-ring feature is omitted as the feature depends on the cutter diameter. All the jobs described by Expert Machinist features can also be described by the features given in Figure 4.5. The parameters of machining features created by Expert Machinist are however inaccessible. Therefore a feature set that permits the access of its feature parameters was needed and in this research the set given in Figure 4.5 are being used. The features can actually be considered as both design and machining features.

4.5.1 Design Features and Machining Features in Pro/Engineer

Design Features in Pro/Engineer are features that are available to the designer to create instances so that a CAD model can be created as an assemblage of design feature instances. These include features such as protrusion, cut, hole, chamfer and round.



Figure 4.6: Component 1

Consider the component shown in Figure 4.7, which can be created using design instances as shown in Figure 4.8. The cross section of the object is drawn and a translational sweep was made to create the object as a protrusion and the design feature used is called a protrusion. Parameters of the created protrusion feature such as the surfaces and their normal's can be obtained using the Application Programmer's Interface called Pro/Toolkit. The model can be accessed by Expert Machinist and Machining Features can be created. Figure 4.9 shows the machining features created by Expert Machinist for the part shown in Figure 4.7. But the parameters of the created machining features are not accessible.

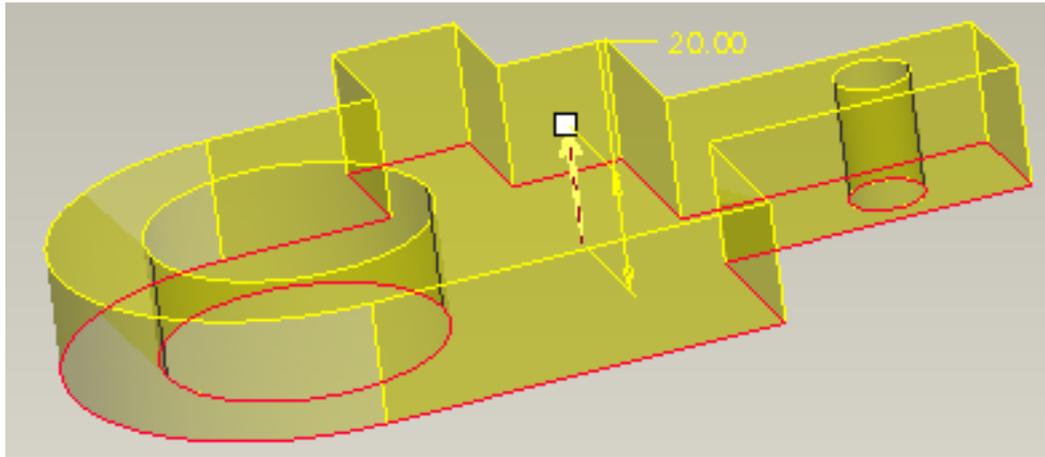
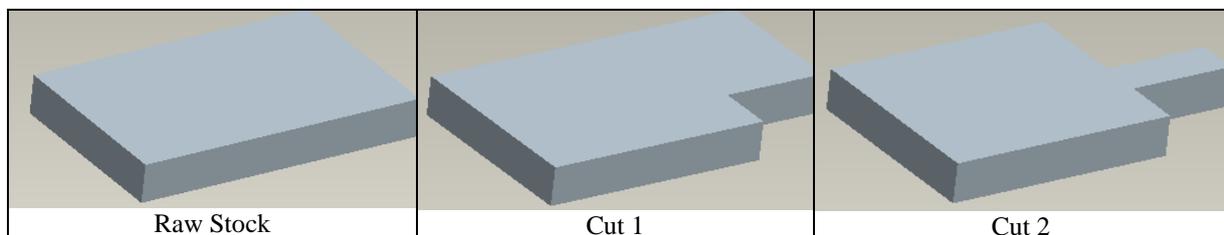


Figure 4.7: Design instance

Setup 1	Setup 2	Setup 3
<ul style="list-style-type: none"> MFG0002.ASM <ul style="list-style-type: none"> EMO_DEF_CSYS MFG002.ASM <ul style="list-style-type: none"> FSETP0 MACH02 ACS0 ACS1 NC_ACS1 ACS2 OP010 <ul style="list-style-type: none"> STEP1 STEP2 STEP3 	<ul style="list-style-type: none"> MFG0005.ASM <ul style="list-style-type: none"> EMO_DEF_CSYS MFG012.ASM <ul style="list-style-type: none"> PRT0009.PRT MFG012_WRK. MACH01 FSETP0 NC_ACS1 ACS0 ACS1 OP010 <ul style="list-style-type: none"> STEP4 TOPROUND1 	<ul style="list-style-type: none"> MFG0006.ASM <ul style="list-style-type: none"> EMO_DEF_CSYS MFG013.ASM <ul style="list-style-type: none"> MACH01 FSETP0 NC_ACS1 OP010 <ul style="list-style-type: none"> DRILL_GROUP_1 DRILL_GROUP_2

Figure 4.8: Machining Features (Expert Machinist) and the Object

Another way of creating the model of the component is by removing material called as cut using CAD software. In this method a block of material called raw stock is subjected to cuts to form the final component.



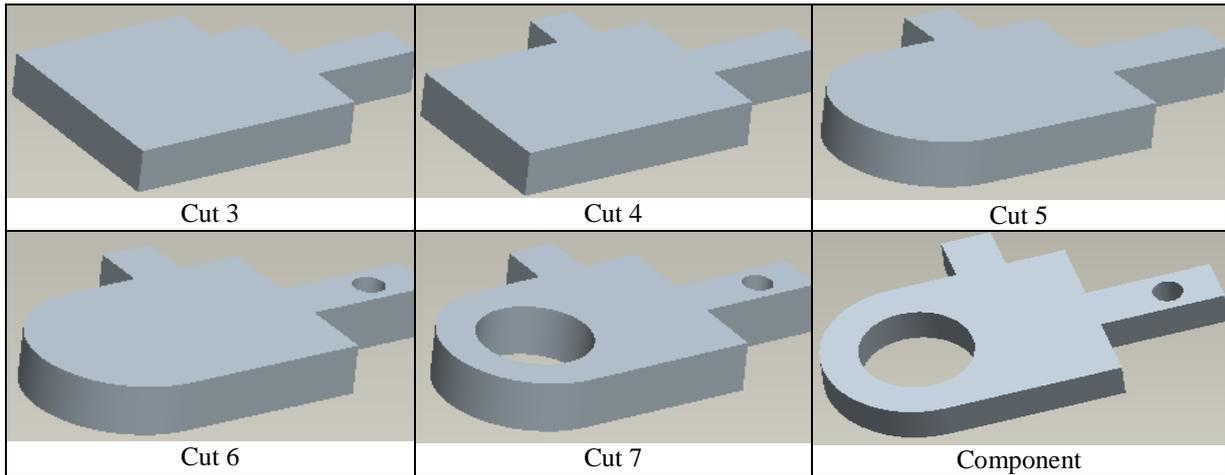


Figure 4.9: Making a Component with Cuts

This process of building the model is shown in Figure 4.10 and the design feature created by Pro/Engineer is given in Figure 4.11. This method however has an advantage because as shown the model is an assemblage of design feature instances, the cuts, and therefore the parameters can be accessed through the API, Pro/Toolkit.

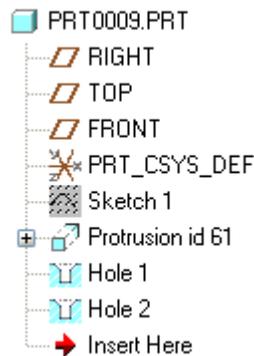
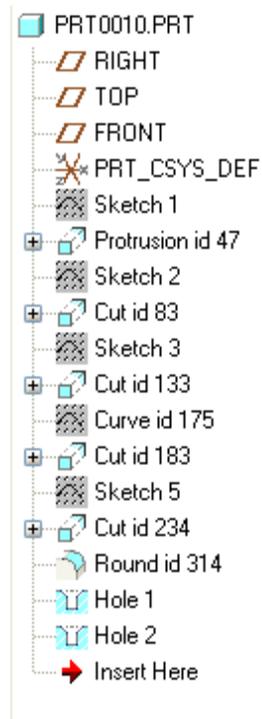


Figure 4.10: Feature Tree Showing the Design Feature Instances

The same job can be described using the features defined in Figure 4.6 is shown in Figure 4.12.



**Figure 4.11: Feature Tree Using the Features Defined in Figure 4.6
(Proposed Machining Features)**

In this research work models created are developed with the features described in Figure 4.6 to build the CAD model (as cuts from a raw stock). The parameters are then extracted using API which is explained in section 4.6.

4.6 Extract Machining Feature Parameters and write them into a file

A model is created as machining instance in CAD, each instance is made of surfaces consisting of entities like vertex and vectors as shown schematically in Figure 4.13.

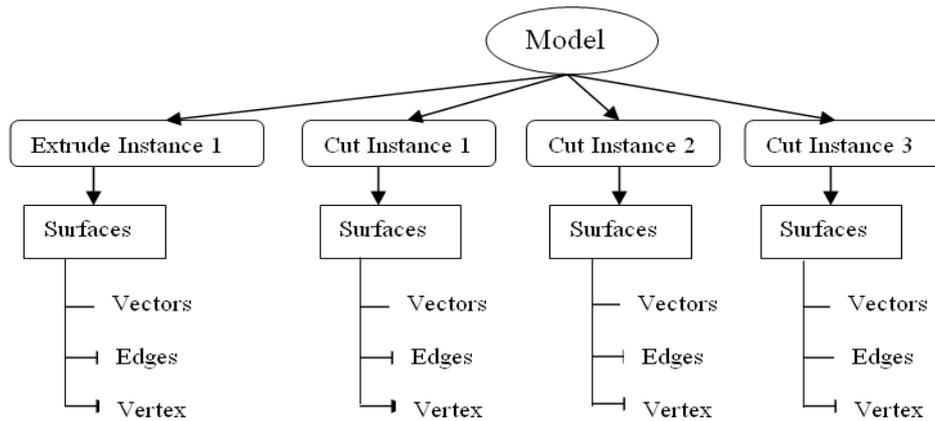


Figure 4.12: Details of Entities Stored

For simplicity a feature can be treated as a volume bounded by surfaces. A surface is bound by edges and edges are bound by vertices. The details of edges and vertices are sufficient to define a surface. However there are other properties that are useful for different applications. For machining applications the surface normal is very useful. If a cut feature is executed it will have several constituent surfaces and each surface will have lists of edges, vertices and a normal vector. However to execute the cut there should be material thus the first feature or the base feature should be a protrusion.

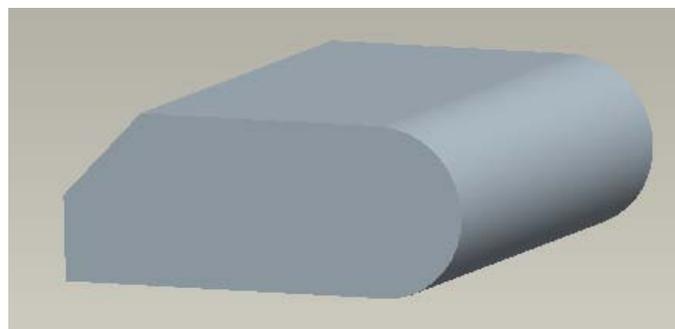


Figure 4.13: CAD Model of Component 2

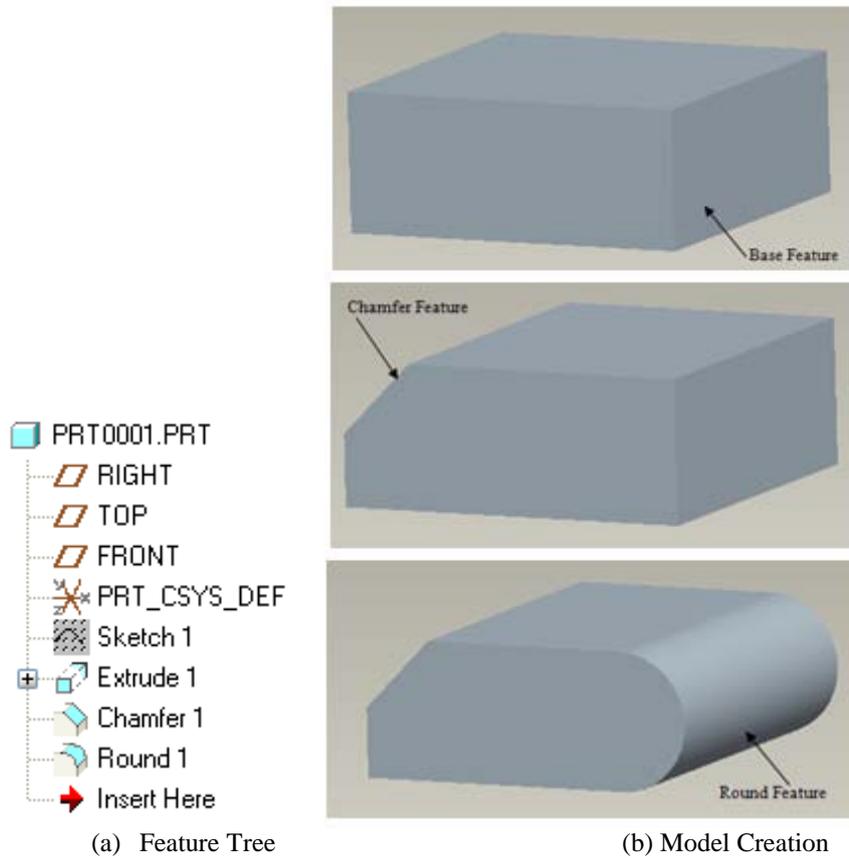


Figure 4.14: Creation of a Feature Based Model and its Feature Tree

Consider the object shown in Figure 4.14 and the feature tree describing its creation shown in Figure 4.15(a). It shows that the object is created with a protrusion, chamfer and round features. The intermediate stages in the creation of the object are shown in Figure 4.15(b). The base feature was the first feature created and it is a protrusion. It has six surfaces, 12 edges and 8 vertices. The chamfer is the first cut. It has five planar surfaces, 9 edges and 6 vertices. The round is the second cut. It has 6 planar surface, 1 cylindrical surface, 15 edges and 10 vertices. The objective in this section is extracting these parameters and writing them into a file. However the vertices, edges and surfaces in the base feature that have been removed are of less significance in these features and only the new surface, edges and vertices created are the important ones and these are the ones that have to be extracted and stored.

4.6.1 Parameters of the Chamfer Feature

Consider the chamfer feature highlighted in Figure 4.16 which was created on a block. Chamfer feature has a created new surface and its entities are 4 vertices, 4 edges and the vectors.

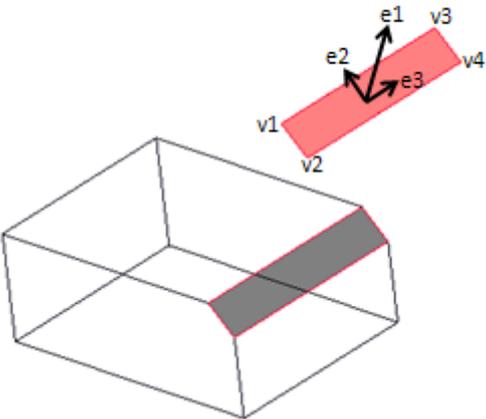
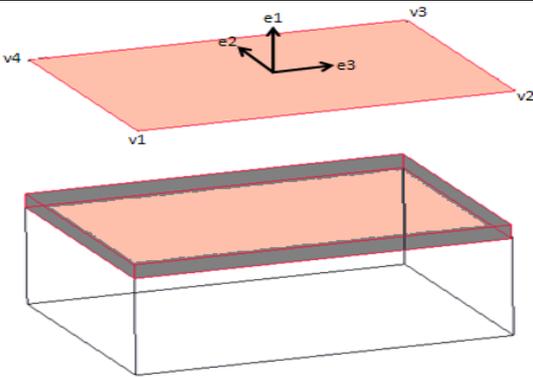
Chamfer Feature	Entities
 <p>(a)</p>	<p>Feature id 1 Plane surface Surface has e1 – Normal Vector e2, e3 – Direction Vectors 4 vertices v1, v2, v3, v4 forming 4 edges v1-v2, v2-v4, v4-v3, v3-v1 Orientation of Chamfer Feature depends on the normal vector of the Plane surface.</p>

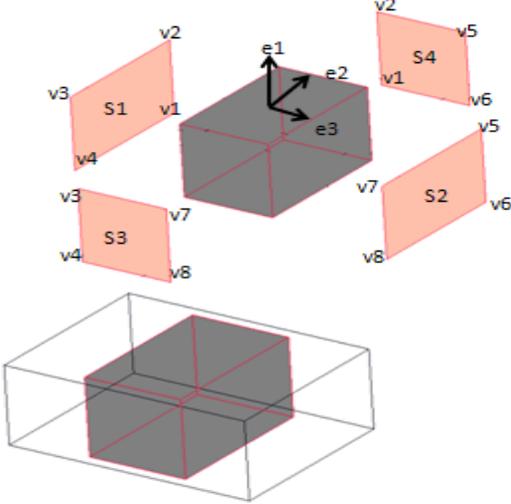
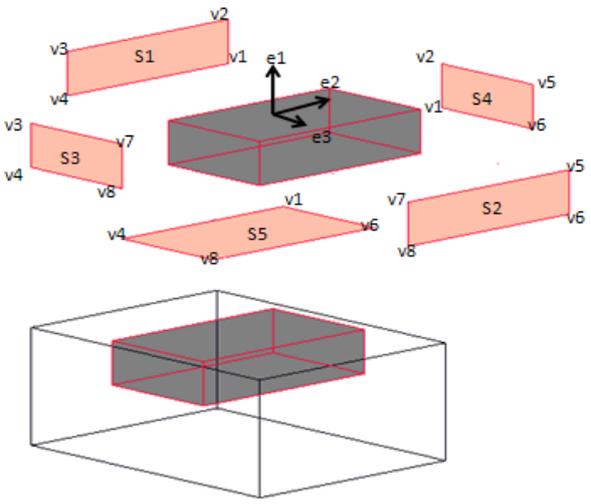
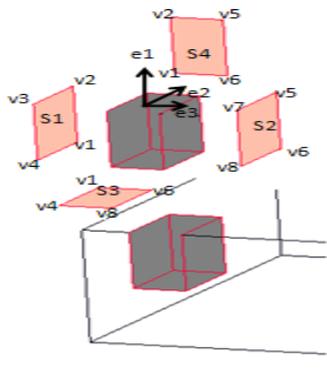
Figure 4.15: Chamfer Feature

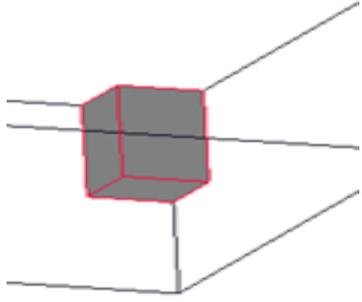
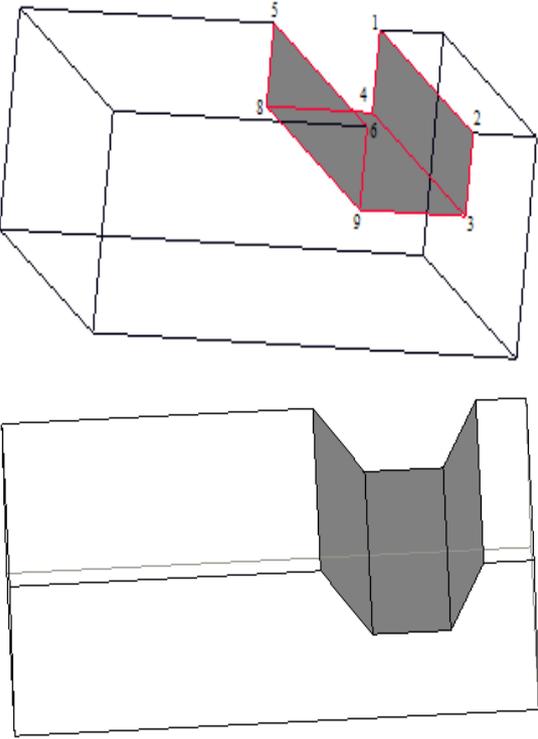
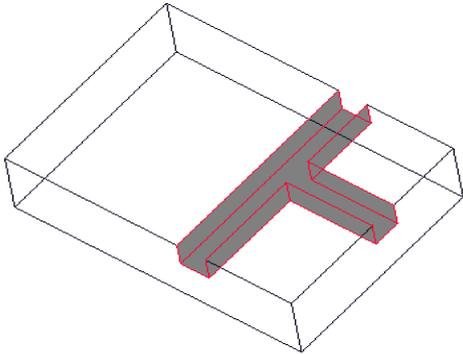
Chamfer feature consist of one surface, having the normal vector and vertex. Using the value of the normal vector the orientation of the chamfer can be identified. With all the four vertex, maximum and minimum points of X, Y and Z are identified which in-turn can be used to identify the range of the axis or the raw stock for the feature can be defined.

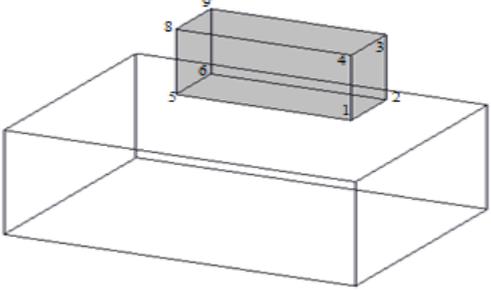
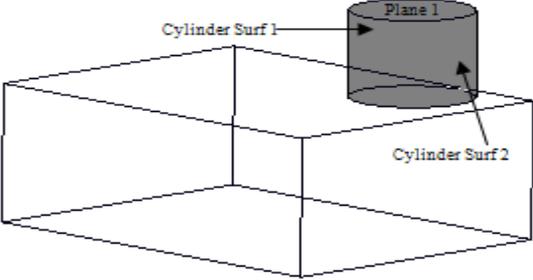
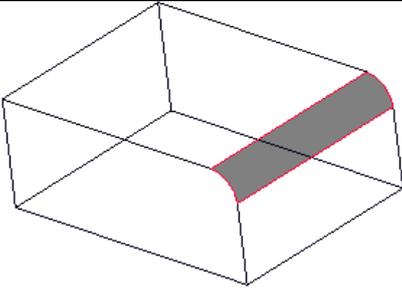
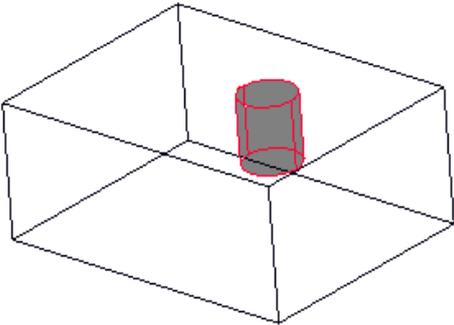
4.6.2 Parameters of the Feature Set

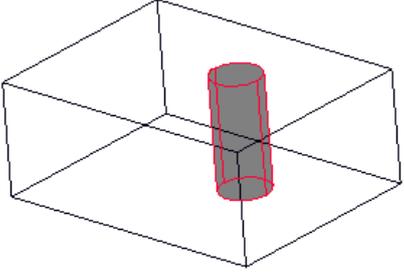
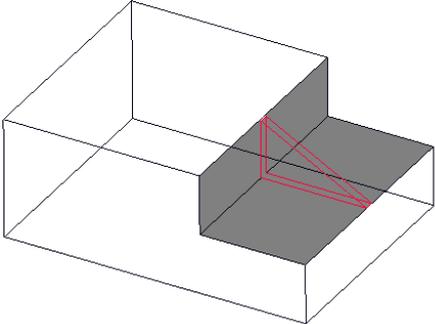
Table 4.10 shows the features and the parameters representing them.

Planar Feature	Entities
	<p>Surf id 91 e1 – Normal Vector e2, e3 – Direction Vectors v1, v2, v3, v4 – Vertex of surface v1v2, v2v3, v3v4, v4v1 – Edges</p>

Pocket Feature (blind)	Entities
	<p>Feature id</p> <p>Consist of Four plane surface S1 – S4</p> <p>Each surface has</p> <p>e1 – Normal Vector</p> <p>e2, e3 – Direction Vectors</p> <p>Orientation of Feature is perpendicular to wall created by four planes formed by 8 vertex.</p> <p>v1-v8, 8 vertex forming 12 edges</p> <p>S1&S2, S3&S4 are parallel to each other</p>
Pocket Feature (Through)	Entities
	<p>Feature id</p> <p>Consist of Five plane surface S1-S5</p> <p>Each surface has</p> <p>e1 – Normal Vector</p> <p>e2, e3 – Direction Vectors</p> <p>Orientation of Feature is the same orientation of the bottom plane's orientation.</p> <p>v1-v8, 8 vertex forming 12 edges</p> <p>S1&S2, S3&S4 are parallel to each other and S5 is perpendicular to both sets</p>
Pocket Feature (Open End)	Entities
	<p>Feature id</p> <p>Consist of Four plane surface S1-S4</p> <p>Each surface has</p> <p>e1 – Normal Vector</p> <p>e2, e3 – Direction Vectors</p> <p>Orientation of Feature is the same orientation of the bottom plane's orientation.</p> <p>v1-v8, 8 vertex forming 11 edges</p> <p>S1&S2 are parallel to each other and S3&S4 are perpendicular</p>
Slot Feature (Open End)	Entities

	<p>Feature id Three plane surface Each surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature is the same orientation of the bottom plane's orientation. 7 vertex forming 9 edges Three planes are perpendicular to each other</p>
Slot Feature	Entities
	<p>Feature id Three plane surface Each surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature is the same orientation of the bottom plane's orientation. 8 vertex forming 8 edges Two plane are parallel to each other and perpendicular to the bottom plane Or Two plane are inclined the bottom plane</p>
Channel Feature	Entities
	<p>Feature id 5 plane surface Each surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature is the same orientation of the bottom plane's orientation. 16 vertex forming 20 edges Intersection of two slots</p>
Planar/Boss Feature (rectangular)	Entities

	<p>Feature id 5 or 6 plane surface Each surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature is the same orientation of the top plane's orientation. 8 vertex forming 12 edges</p>
Planar/Boss Feature (Cylindrical)	Entities
	<p>Feature id 2 cylindrical and 1 plane surface Each surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature is the same orientation of the top plane's orientation.</p>
Round Feature (Prismatic)	Entities
	<p>Feature id 1 cylindrical surface Surface has e1 – Normal Vector e2, e3 – Direction Vectors 4 vertex forming 4 edges Orientation of Feature is the same orientation of that of cylindrical surface.</p>
Hole Feature (Through)	Entities
	<p>Feature id 2 Cylinder and 1 Plane surface Each Surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature is the same orientation of that of bottom Plane surface.</p>
Hole Feature (Blind)	Entities

	<p>Feature id 2 Cylinder and 1 Plane surface Each Surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature is perpendicular to the orientation of cylindrical surface.</p>
Rib Feature/Combination of 2Step and 1Chamfer	Entities
	<p>Feature id 5 Plane surface Each Surface has e1 – Normal Vector e2, e3 – Direction Vectors Orientation of Feature depends on the chamfer feature created between the two step features.</p>

Thus the feature set used in the research work are tabulated in Table 4.10 have a definite dataset associated to each one of them.

4.7 Read and Process Parameters from the file and identify Features for a Single Setting

Features are first identified, and then depending on the type of cut and number of surface they are grouped into Machining Features. Individual surface entities of the machining feature are collected and analyzed to identify two parameters a) Setup and b) Range of the feature.

Number of Setup for the component can be identified from the number of Machining Feature and its orientation. Orientation of the machining features depends on bottom surface orientation, which can be identified from its surface normal. Few machining feature like blind feature does not consist bottom surface, then their orientation is identified from the existing surface. If the surface normal of different machining feature have the same value, then the orientation of the features are in the same direction, if different they require additional setup for each different group of values. The process of identifying number of setup is shown in Figure 4.17.

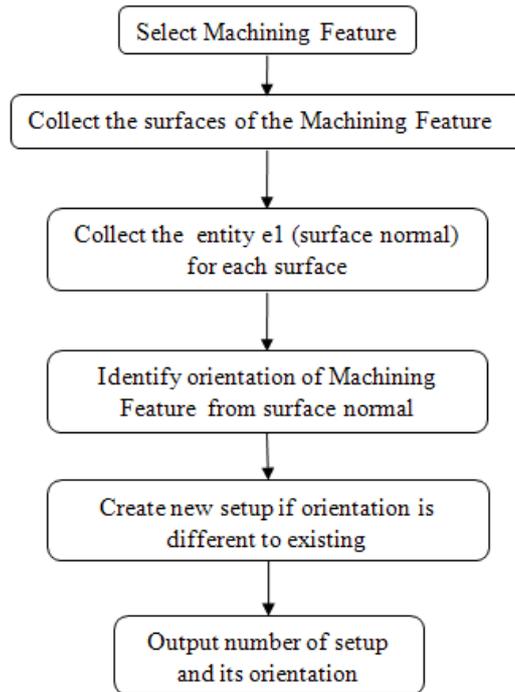


Figure 4.16: Process Flow chart to identify number of Setup

Range of the Machining Feature can be calculated from vertex entities of the surfaces which creates the machining feature as shown in the flow chart in Figure 4.18. Calculating maximum and minimum limits of all the vertices that created the feature, the range of the machining feature can be identified. Grouping all the of Machining Feature's range, the working area required for the component can be found.

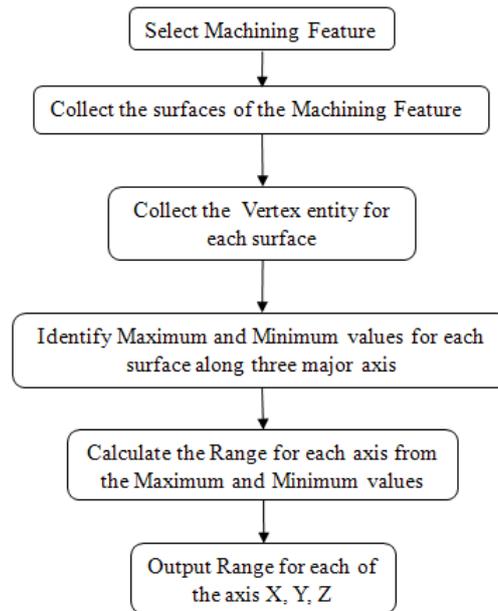


Figure 4.17: Process Flow chart to identify Range of X, Y, Z axis

4.8 Further inputs and generation of alphanumeric code

Orientation and limitation of machining features would not be sufficient to select the right machine tool for machining. Further details are required as input for optimizing the selection process like (a) Spindle details (Speed and feed rate), (b) Cutting Tool (changers and carousel), (c) Accuracy, (d) repeatability and (e) Fixture details.

Spindle details are important as they holds the cutting tool, the speed and feed are vital accept that are required for finish and removal of material. High speed and low feed produces a high surface finish and low speed and higher feeds are used for the faster material removal. Depending on the required surface finish and need of the finished material the spindle details are requested from the user. It is represented as the spindle details of machine tool feature.

Automation of the process with *Cutting tool* and *pallet changer* details are also considered as input to reduce the setup time and quick change. Certain machining features can be done quickly with use of more than one cutting tool on the other hand certain machining features might only use one tool. The number of tools and type of the tool change is not identified as it would require other parameter like the material selection, mass property and surface finish of the component but rather considered as an input.

Accuracy of positioning to higher standard is achievable with present day machine tools, but not all machining operation requires a high standard. It is important to consider as higher accuracy may take longer machining time from a high end machine tool. Accuracy is also taken as input as this could vary depending on the type of finish and requirement of the component.

Repeatability in modern machine tool is one of the factors that influence the accuracy. Repeatability is considered for a high accuracy machining component as low repeatability might cause a higher tolerance to the finished component. Repeatability is considered as input for selection of machine tool in this research work.

Fixtures are used to hold the machining component in required position for tool to position conveniently and to machine faster. The fixture can sometime come into machining path, so it is important to consider the location of fixture and to identify the probability of feature blocking any of the machining features. If the fixture creates obstruction for machining any machining features it become inevitable to move the machining features into different orientation or to break the orientation into two setups. Different types of fixture are considered as input for selection of suitable machine tool, identifying special fixture need and there interference with machining is not considered in this research work.

The various factors extracted from the machining features and the acquired by user input are used to create alphanumeric code.

4.9 Comparing and marrying the alphanumeric code

There are two sets of alphanumeric codes generated first one from the machining component features and the second code consisting details of machine tool features. The code from machining component features consists of two sections a) user input and b) capacity. The capacity details are extracted from components using API program and the other required details are requested from user. Machine tool features are created as alphanumeric code from alphanumeric strings of machine details. This matching of both the alphanumeric codes is shown in Figure 4.19.

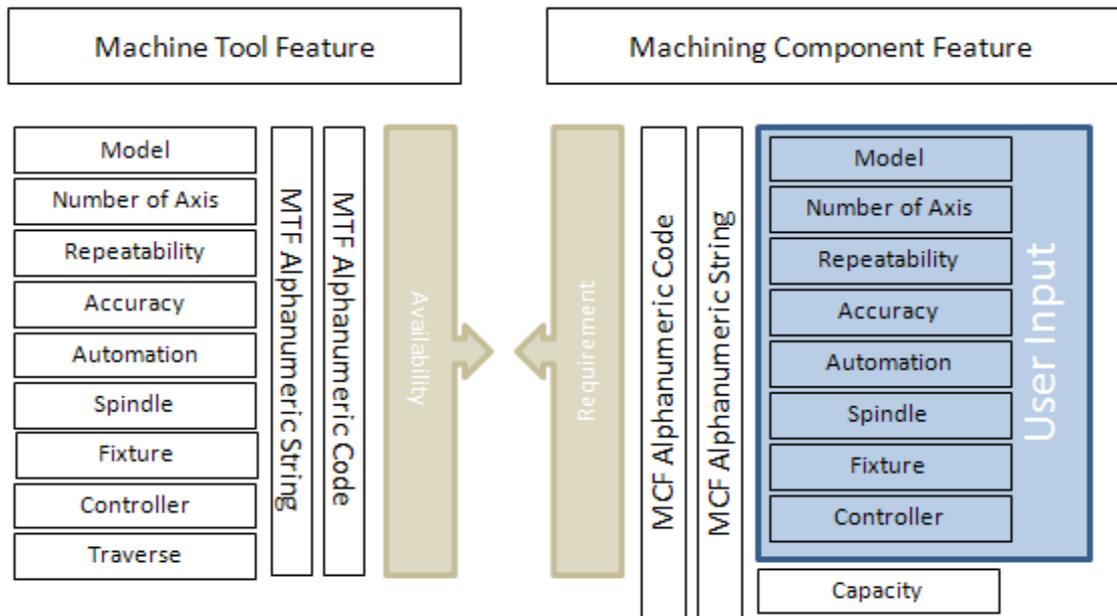


Figure 4.18: Intended marriage between alphanumeric code

4.10 Obtain requirement from the user and select the Machine tool

The intended alphanumeric code is not complete without a user interface, where the details of the machining features can be contributed. The interface should be able to request the details that are identified in chapter 4.2 for generation of alphanumeric code for the sub-system. The interface on the other hand should also interact with a temporary database which stores the details of the machining feature. The details are formatted together to create the alphanumeric code when requested for machining features.

The second interface for the machine tool's alphanumeric code should be able to interact with the database of the machine tools and generate alphanumeric code for them. The interface should also be able to create, modify, delete and query the machine tool database as requested by the user.

A third interface would be created that would use the alphanumeric code of the machining features to query the database of the machine tool. The results of the selected machine tools would be suitable for that particular machining component and its features. The selected machine tools would be displayed as list, and further details of individual machine tools would be displayed.

Chapter 5: Implementation

5.0 Introduction

This chapter explains the implementation of methodology outline in the chapter 4 as shown in Figure 5.1 using Microsoft Office Access as the database, Pro Engineer as the CAD software, and Pro/TOOLKIT as the Application Program Interface. As outlined in the methodology a database with all necessary details of machine tools, each with defined alphanumeric strings to generate the alphanumeric code has been created. In the similar way software has been developed to query the CAD model which is created as an assemblage of cut features.

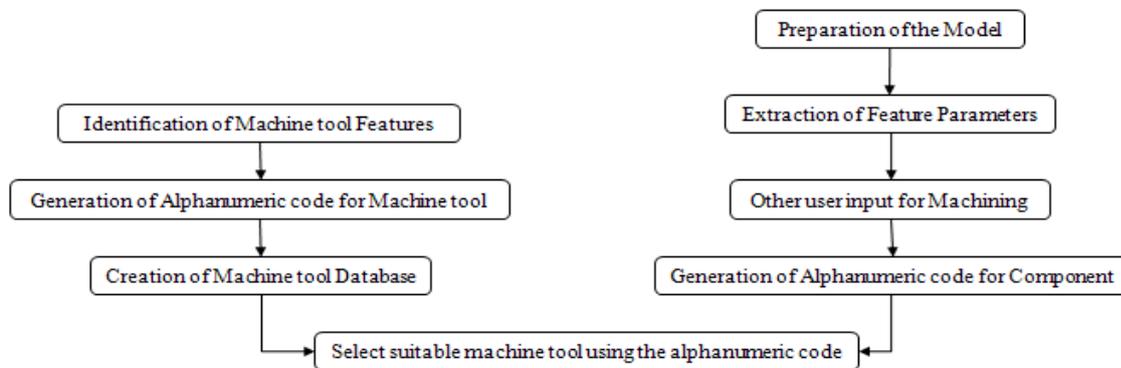


Figure 5.1: Process flow chart for selection of machine tool

The results of the query would extract the feature properties using Application program interface, Pro/TOOLKIT. The data collected from the Pro/TOOLKIT is written into a flat file database in Microsoft excel. Details from the structured database is read using a second software program created using Visual Basic (VB) for analysing the data to (a) identify the number of setups (b)decide the orientation of the machining feature and (c) to determine the range for machining the features. Further the VB software would request the user to input other machining details before the alphanumeric code for the given component is created. The alphanumeric code thus generated is used as the key to search the machine tool database and this extracts suitable machine tools.

5.1 Essential features of a Machine Tool

Machine Tool features identified in chapter 4 are entered into the database as alphanumeric strings. The identified alphanumeric strings are represented as follows:

- *Make and model*: This string would consist, details of Manufacture name and model as one variable. The length of the string is not set as it can be varied for diverse range of models and manufacture, to accommodate all possible combination and length this is kept to the maximum possible length in the data field. Figure 5.1 shows few different machine tool model and manufacture with their representation string.

Presently machine tools are identified using make and model specified by their manufacturer. This can be incorporated as an alphanumeric string for the alphanumeric code, which in-turn would help the machinist to select a specific manufacturer's model for machining.

Table 5 1: Manufacture Name & Model String

Manufacture name and Model Number	String
HURCO VM1	HURCO-VM1
HARDINGE VMC 480 P3	HARDINGE-VMC-480-P3
HAAS VF-2TR	HAAS-VF-2TR

- *Number of axis*: Total number of traverse and rotary motions performed by the machine tool is represented in this string. String consists of two digits numeric variable which can accommodate the variation of motions from 1 to 99. Table 5.2 shows the model and the number of axis representation as string.

Table 5.2: Axis String

Manufacture name and Model Number	Axis	String
HURCO VM1	3	03
HARDINGE VMC 480 P3	3	03
HAAS VF-2TR	5	05

Number of setups in a machining operation can be reduced by increasing the freedom of the machine tool. Presently number of axes in a machine tool is identified by the model type which can be deceiving, as retrofit or optional additions in the same model can alter number of axis.

- *Repeatability*: Repeatability in microns is represented as 2 digit numeric variable that can represent the machine tools capability. Table 5.3 represents the repeatability value in string.

The ability to re-visit to a same location has implication a) from which direction has the axis motion have been made and b) if the point is approached by two motions of two different directions such as work table and cutting tool. A good repeatability is difficult to achieve as it involves hysteresis of mechanical motions, and feedback. Repeatability is one of the important factor that is considered for high precision machining. Repeatability of a machine tool can be found in the details of the machine tool but are not normally displayed with the machine model and make.

Table 5.3: Repeatability String

Manufacture name and Model Number	Repeatability	String
HURCO VM1	0.0025mm	25
HARDINGE VMC 480 P3	0.002mm	20
HAAS VF-2TR	0.0025mm	25

- *Accuracy*: Accuracy in microns is represented as 2 digit numeric variable that can represent the machine tools capability. Table 5.4 represents accuracy value as strings.

Table 5.4: Accuracy String

Manufacture name and Model Number	Accuracy	String
HURCO VM1	0.005mm	50
HARDINGE VMC 480 P3	0.005mm	50
HAAS VF-2TR	0.002mm	20

Accuracy is necessary for positioning the cutting tool and job at the right position for accurate machining as this defines the machines ability to position the axes which it has not visited before. Accuracy of machine tool can be found from the details supplied by the manufactures but cannot be identified from the model or make.

- *Automation*: Consist of two set of string a) tool changing system and b) pallet changing system. First set represent the pallet and the second represents the tool systems. Each set of string is normally made up of five characters, the first saying

whether it is manual or automated, the second whether it refers to tool or pallet and the remaining three numeric digits representing the number of tools or pallets. If there are multiple systems a numeric character is introduced to represent more than one option. Table 5.5 represents the string for pallet and Table 5.6 represents the string for tool.

Automation in a machine tool would reduce setup timing that would be incurred due to changing the cutting tools or pallets. Automation details are given by the manufacturers of the machine tool but they are not represented with the model number or name.

Table 5.5: Pallet Changer String

Manufacture name and Model Number	No. of Pallet	Type of Change	String
HURCO VM1	1	Manual	MP01
HARDINGE VMC 480 P3	1	Manual	MP01
HAAS VF-2TR	1	Manual	MP01

Table 5.6: Tool Changer String

Manufacture name and Model Number	No. of Tool Carousel	Type of Change	String
HURCO VM1	16	Manual	AT16
HARDINGE VMC 480 P3	16	Manual	AT16
HAAS VF-2TR	20	Manual	AT20

- Spindle details:* String is made up with combination of character and numbers. The first character will represent the axis of orientation of the spindle followed by numeric digits. Numeric digits would represent the feed rate of the cutting spindle followed by number of spindles separated by a hyphen. Alphabet ‘S’ follows the numeric digits to represent the spindle details and to separate from the next set of numeric digits which represent the speed of the spindle. Spindle speed is represented as rpm/100 to reduce the length of the alphanumeric string, and to accommodate any high-speed spindles possibility in future. In case of multiple spindles having same parameters numeric digit is added in front of the symbol representing the axis orientation. Multiple spindles with varying parameters are represented as separate string appended using the symbol ‘+’. Table 5.7 represents the spindle features string.

Spindle is a crucial component in a machine tool as this holds the cutting tool for machining. The feed and speed of the spindle is useful for deciding the raw stock material on which the component can be machined. The information about the spindle are represented briefly in the details given by the manufactures but multiple spindles or their direction are not normally represented in the name or model description.

Table 5.7: Spindle String

Manufacture name and Model Number	Axis or Orientation	Max Feed Rate for Cutting	No. of Spindle	Spindle Speed in rpm/100	String
HURCO VM1	Z	19m/min	1	80	Z19-1S80
HARDINGE VMC 480 P3	Z	12m/min	1	100	Z12-1S100
HAAS VF-2TR	Z	16.5m/min	1	75	Z16.5-S75

- *Fixture*: Fixture details or the type of fixture present in a machine tool is abbreviated to four character string.

Fixture details are important feature that is necessary to secure and hold the component for machining. Fixture can be created for a particular component or standard fixture like T-Slots, clamps can be used.

- *Controller*: Controller model is abbreviated to four character string for representation. Table 5.8 represents the controller strings of few different controllers.

A controller supplants a machine tool operator and regulates the motions, spindles, feed and subsystems of machine tool in tandem. Depending on the number of subsystem to be regulated simple to complex the control systems are used. Controller model are not represented on the machine tool model or the name as these are optional but for a machining a better control system can provide a higher level of finish on a component.

Table 5.8: Controller String

Manufacture name and Model Number	Controller	String
HURCO	Hurco	HURC

VM1		
HARDINGE VMC 480 P3	Fanuc	FANU
HAAS VF-2TR	Haas	HAAS

- *Motion blocks*: Each of the motion performed by the machine tool can be considered as separate blocks. Each block is represented as a string with combination of one character followed by numeric digits. The first character will represent the type of motion provided by the block and the following digits represent the motion value. For a traverse motion value would be distance in mm and for rotation in angle. The numeric digits are not restricted as to accommodate larger axis of motions. Table 5.9 represents the all the motion of the machine tool as string.

Table 5.9: Motion Block String

Manufacture name and Model Number	X Axis Travers in mm	Y Axis Traverse in mm	Z Axis Traverse in mm	a rotation angle	b rotation angle	String
HURCO VM1	660	356	457	-	-	X660:Y356:Z457
HARDINGE VMC 480 P3	480	400	430	-	-	X480:Y400:Z430
HAAS VF-2TR	760	508	508	120	369	X760:Y508:Z508:a 120:b:360

Some of the machine tool represents the axis traverse of the machine tool in their model name which may be X, Y or Z. It is important to define the machining space depending on the X, Y & Z traverse distance. Inclusion of motion traverse distance in the code and the rotational angle would be useful to identify the machining space.

- *Other Systems*: Coolant, swarf & dust removal systems are represented using three characters respectively. Presence or absence of the three systems is flagged by 'P' or 'F'. Any further inclusion of any other system can be include as the forth and subsequent character along side of the existing string. Table 5.10 represents the various subsystems present in a machine tool and its representation string.

By product of machining would create chip and heat between tool and raw stock. Coolant is necessary for absorbing the heat dissipated and swarf and dust removal system of chips.

Subsystems are not represented with the make and model name of the machine tool manufactures presence or absence of these systems would help to remove the by-products of machining.

Table 5.10: Subsystem String

Manufacture name and Model Number	Coolant System	Swarf Removal system	Dust Removal System	String
HURCO VM1	Present	Absent	Absent	PFF
HARDINGE VMC 480 P3	Present	Absent	Absent	PFF
HAAS VF-2TR	Present	Absent	Absent	PFF

5.2 Establishment of Alphanumeric Code

The alphanumeric strings created are systematically assembled in sequence, starting from the first string consist of ‘Make and model’ to ‘Subsystem’ as shown in Table 5.11 which would create the alphanumeric code of the machine tool. Each string is separated using colon when represented in the alphanumeric code. Motions string are represented in the code starting from component string to the cutting tool string which form a loop. Some machine tools might have more than one spindle which would create multiple loops which can be represented using ‘+’ symbol were the loop separates. The static block or the stationary block along the loop of the motion is represented as ‘O’ which is included onto the motions string which the stationary block carries. Representation of motion string and the location of the stationary block are crucial as this can be used to identify the type of milling machine structure as described in Table 5.12.

Table 5.11: String Sequence

Manufacture and model	No. of Axis	Repeatability	Accuracy	APC	ATC	Spindle details	Fixture	Controller	Motions	Sub system

Table 5.12: Location of Stationary Block

Location of Stationary block	Type of milling Machine
At the start of motion string	Gantry or Column

After X,Y motion string combination	Knee milling
-------------------------------------	--------------

Alphanumeric code not only highlights the capacity and features but can also identify type of machine tool by the orientation of the spindle.

5.3 Creating database and generating alphanumeric code for Machine Tool Feature

Figure 5.2: Visual Basic program for database

The various features required for generating the alphanumeric code for machine tool are collected to create a database of machine tool. Interface program created using Visual Basic would request the user to enter the details of machine tool. Figure 5.1 shows the interface program created using Visual Basic. Using the features, the software would create the string to generate alphanumeric code. The interface software consists of three parts each separated by a vertical line.

First part of the interface software would request user to enter details like a) make & model and b) motion details. Motion details in the first part are entered starting from the component to the cutting tool as instance of block which performs the motion. The block of information would consist of a) axis convention, b) the motion value, and c) if they branch out.

- a) Axis convention: The nomenclature of the axis would follow the same convention as used by right hand coordinate system and in case of non motion block it is represented as 'O'.
- b) Motion value: Maximum traverse motion value is entered in mm and for rotational maximum possible rotation angle is entered.
- c) Branch out: Following the block of motion from component to machine tool, some machine tool would consist two spindle heads as shown in Figure 4.3. Representation of block from component to cutting tool would branch after the base motion. After the motion of the base the loop separates. Each separated loop from the base to the cutting tool is shown with a '+' as join to the base motion.

The number of motions block including the stationary block is restricted to 11 in the created software interface, which can be further increased if required.

Second part would request for the user to enter details of a) spindle, b) automation, c) accuracy, d) repeatability e) Fixture, f) Controllers and g) other system present in the machine tool. Values are entered by the user on the interface form of the software are first validated for the type and character format. On validation of all the feature specific alphanumeric string are created at the back end of the software to generate the alphanumeric string. The entered feature values and generated alphanumeric code of the machine tool are updated on to database by the interface program.

The third part of the interface would request for any picture of the machine tool that can be load as with the location path. The created software would not only allow the user to add new records of machine tool to the database but also view, modify or delete any of the existing records from the database.

Table 5.13: Alphanumeric Code

Dugard-VMC660:	03:	30:	40:	MP01:	AT24:	Z30-1S80:	STAN:	HEID:	X660:	Y550:	0Z510:	PPF
Manufacture and model	No. of Axis	Repeatability	Accuracy	Pallet changer	Cutting tool	Spindle details	Fixture	Controller	X traverse	Y traverse	Column and Z traverse	Sub system Coolant, Swarf, Dust

Consider the Machine tool features of Dugard VMC660 in the appendix ##, its features details are tabulated in table 4.4 and the representation of Machine tool as alphanumeric code is represented in Table 5.13.

5.4 Some Machine Tools and their Alphanumeric Codes

The table 5.14 represents alphanumeric codes of commercially available machine tools.

Table 5.14: Example of Machine tool and its Alphanumeric Code

Machine tool	Alphanumeric Code
 <p>4 Axis Vertical Machining Centre</p>	<p>DIXI-DHP50:04:90:09:AP02:AT100:Z24-1S120:STAN:HEID:a360:X700:Y700:0Z700:PPP</p>



6 Axis Vertical Machining Centre

BOKO-WF3/12:06:20:10:MP01:AT40:W10-
1S31.5:STAND:FANU:c360:X1800:Y1200:0Z860:b90:w
300:PPF



Twin Spindle 3 Axis

EMAG-S0322:04:20:20:MP01:AT24:Z20-
2S50:STAN:FANU:X600:Y500:0Z600:PPF



Twin Spindle 5 axis

EMAG-BAS03:06:20:20:MP01:AT24:Z20-
2S50:STAN:FANU:c360:a90X60:Y500:0Z600:PPF





5.5 Preparing the CAD model suitable for machining features identification

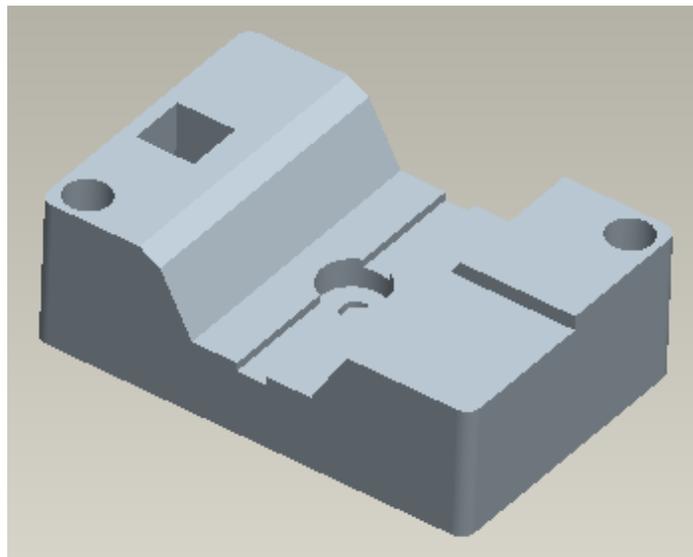


Figure 5.3: Component

Consider the component shown in Figure 5.3, which has to be modelled in Pro Engineer. There can be various combination of modelling instance that can be used to create the model. As the machining process removes material from the raw stock it is crucial to create the model as instance of material removal only and not addition when modelling in Pro Engineer. Figure 5.4 shows the creation of the component shown in Figure 5.3 as instance of material removal. These design instances in Pro Engineer which removes material can be a CUT, CHAMFER, HOLE or ROUND.

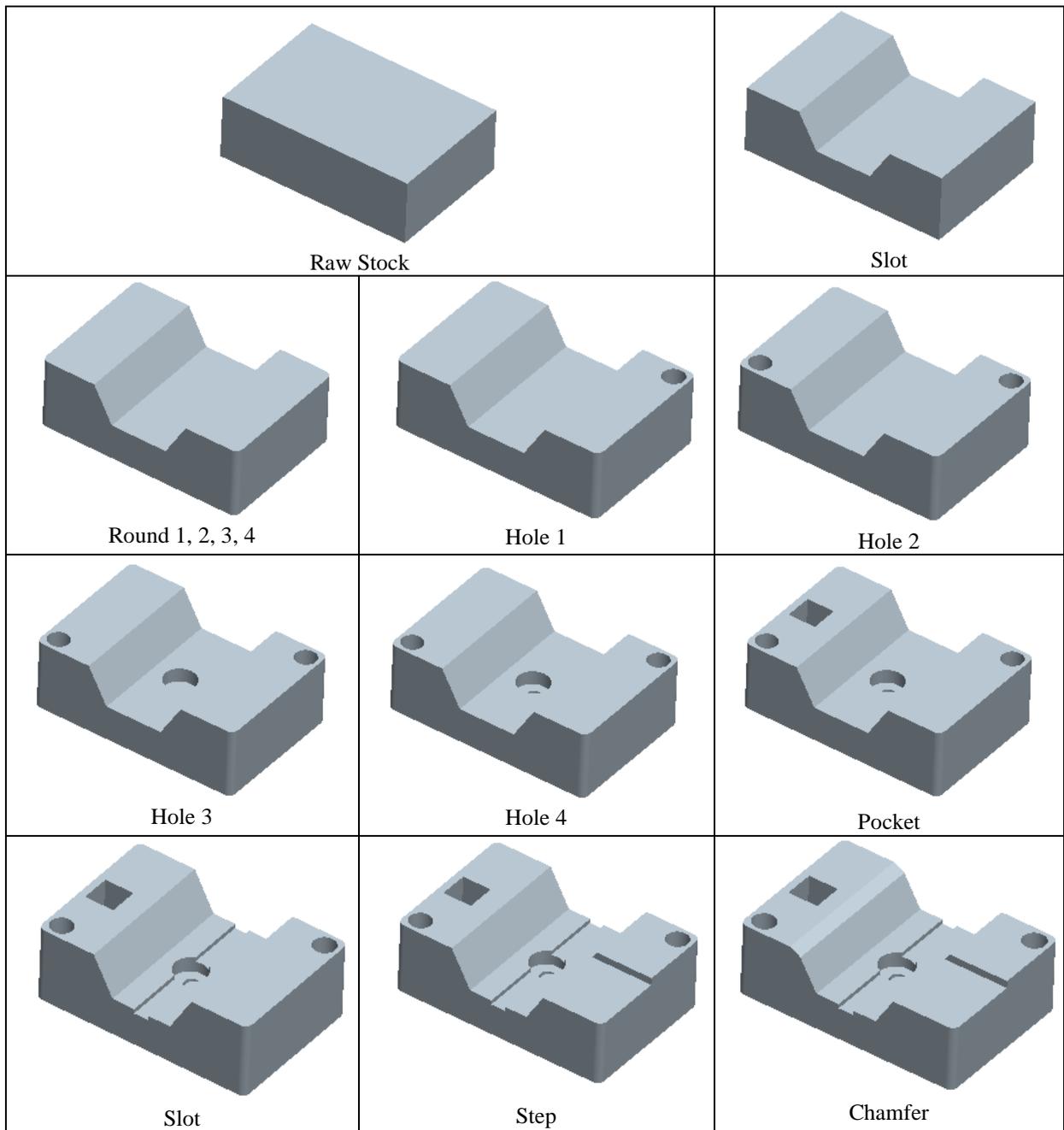


Figure 5.4: Preparation of model using material removal

Design instance in Pro Engineer is accessed by the created Application Program Interface software using Visual C ++, that uses functions provided by Pro/TOOLKIT. Considering the design instance of Chamfer which removes material and creates a single plane surface, and Round would create a single cylindrical surface whereas the Cut can produce both cylindrical and plane surfaces depending on the sketch created for the cut, similarly hole instance can produce both surface depending whether it's a simple, complex, through or

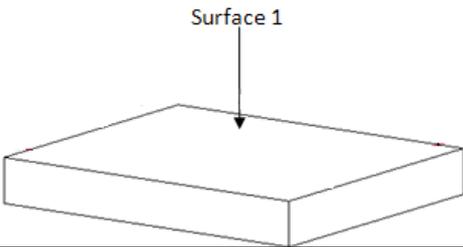
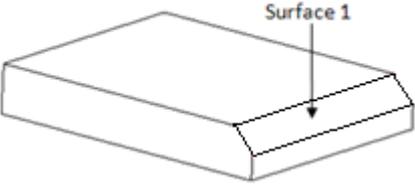
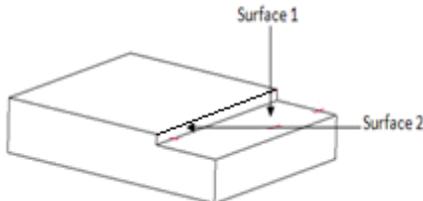
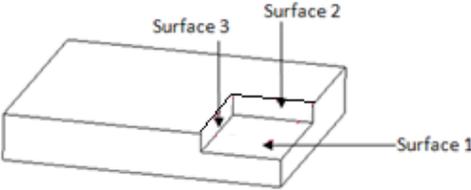
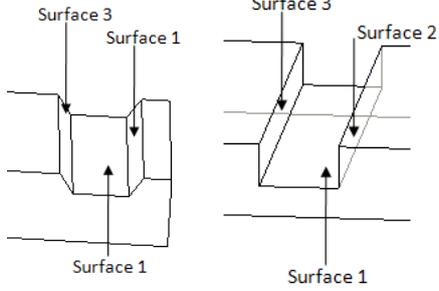
Blind. Using the created API software the design instance are accessed and analyzed to identify them as machining feature which is discussed in session 5.6.

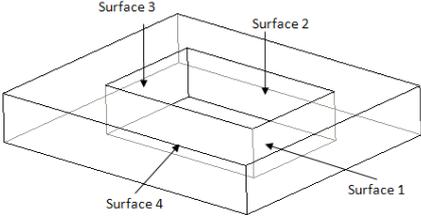
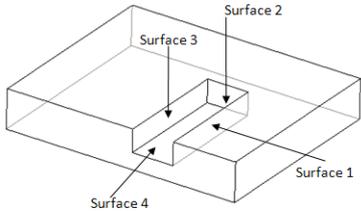
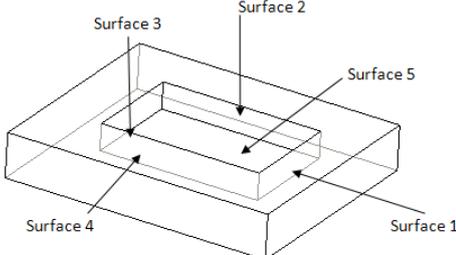
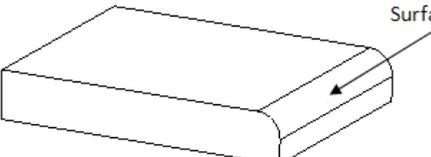
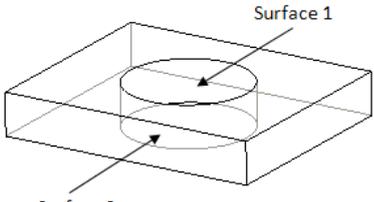
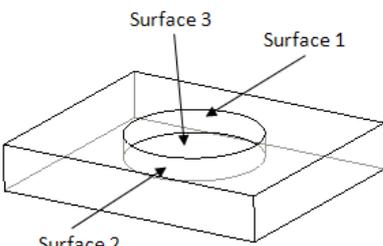
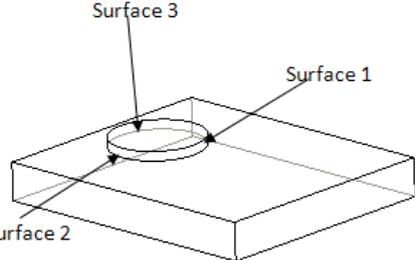
5.6 Extract Machining Feature Parameters and write them into a file

The machining features considered for the research work considered in Figure 4.6 were identified using API software. The API software created using Pro/TOOLKIT functions will a) identifies each machining feature b) extract data of surface and c) write them to structured file.

Machining features are identified depending on the number of surfaces and type of surfaces (plane or cylindrical). The Table 5.15 shows the creation of various machining feature which are formed by plane and cylindrical surfaces. Each surface is in-turn made up of edges and vertices, the details of edges and vertices are extracted using API software and dumped into a file.

Table 5.15: Machining Feature and its Surfaces

Surface	Feature	
1 Plane		
	Planar	Chamfer
2 Plane		
Step		
3 Plane		
	Open Slot	Slot

4 Plane		
Through Pocket		Open Pocket
5 Plane		
Pocket		
1 Cylindrical		
Round		
2 Cylindrical		
Blind Hole		
2 Cylindrical + 1 Plane		
	Through Hole	Boss

5.6.1 Creation of Menu

On execution of the created API software, it would create a menu along side of the existing Pro Engineer's tool bar menu, the created menu 'Machining Features' and submenu is shown in Figure 5.5.

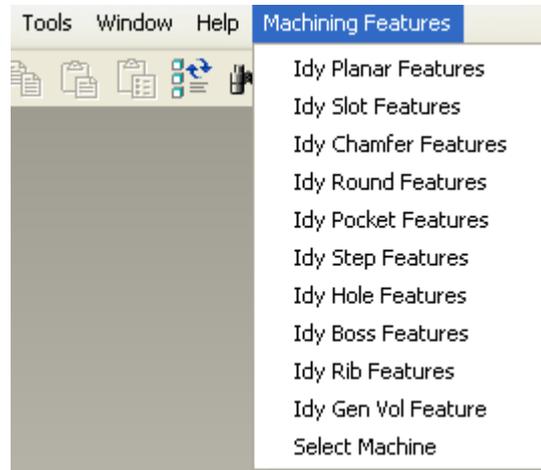


Figure 5.5: Created Menu in Pro Engineer

API software is created using Visual C ++ compiler in Dynamic Linked Library mode. The software is created in DLL mode so that required library functions are first compiled and stored in a library with extension .DLL. Using the synchronous application of Pro Engineer the .DLL file is loaded using an intermediate file called registry. The registry file is read through the auxiliary application from Pro Engineer to execute the API software created. The loading of the registry file through the auxiliary application is shown in Figure 5.6.

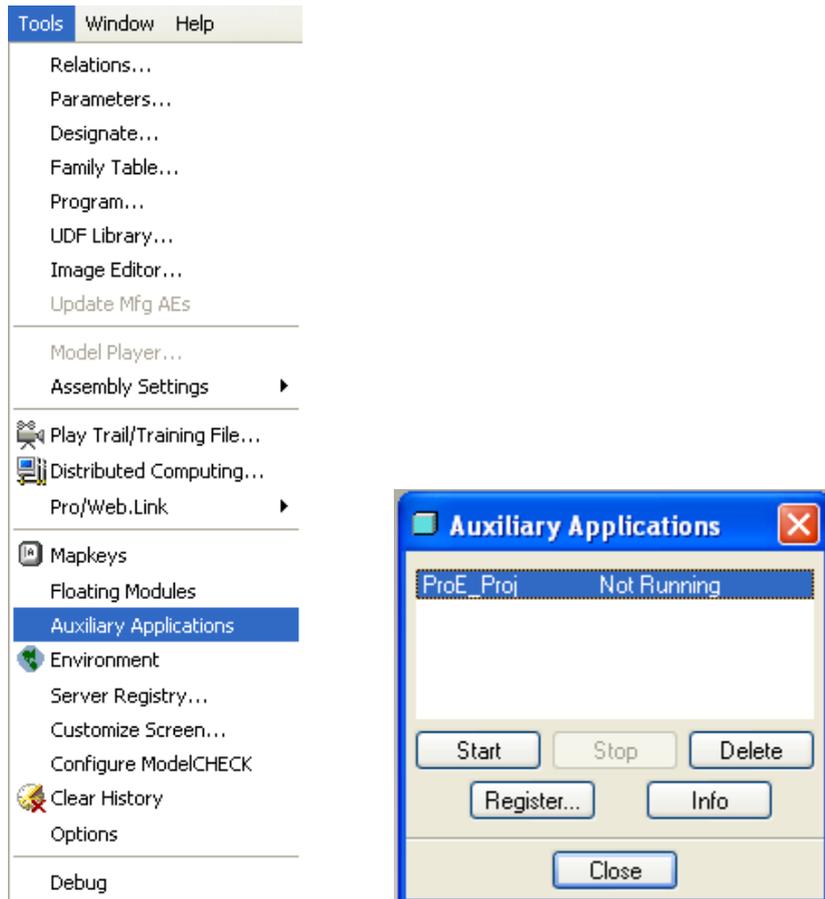


Figure 5.6: Starting Auxiliary Application in Pro Engineer

5.6.2 Selection of Submenu

On selection to identify any particular machining feature from the sub menu, the API software would then highlight the edges of the surfaces that form the machining feature. Further the user would be prompted to select the surfaces which create them. After selection of surface, any further occurrence of the same machining feature would be highlighted again and the user prompted unless there is no further instance of the same machining feature.

Consider the component shown in Figure 5.7(a) consisting of single slot feature. On selection to identify slot feature from the sub menu, the API software identifies the slot feature and highlights the edges as shown in Figure 5.7(b).

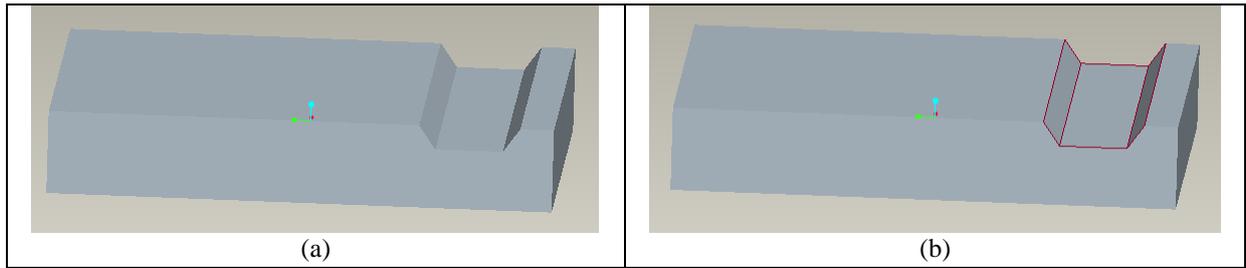


Figure 5.7: Component with Slot Feature

After the highlighting the machining feature by the software it would be prompted with a message box to the user to select the surfaces whose edges are highlighted. The process of selecting surface is done manually to avoid any conflict which might arise due to intersecting of surface. The process of surfaces selection for a slot feature is shown in Figure 5.8. The process of selection is done from the bottom surface or the surface that orientates the feature followed by side surface which forms the wall this is followed for all the machining features. This process of selection is followed to create uniformity in dumping the data of the surfaces.

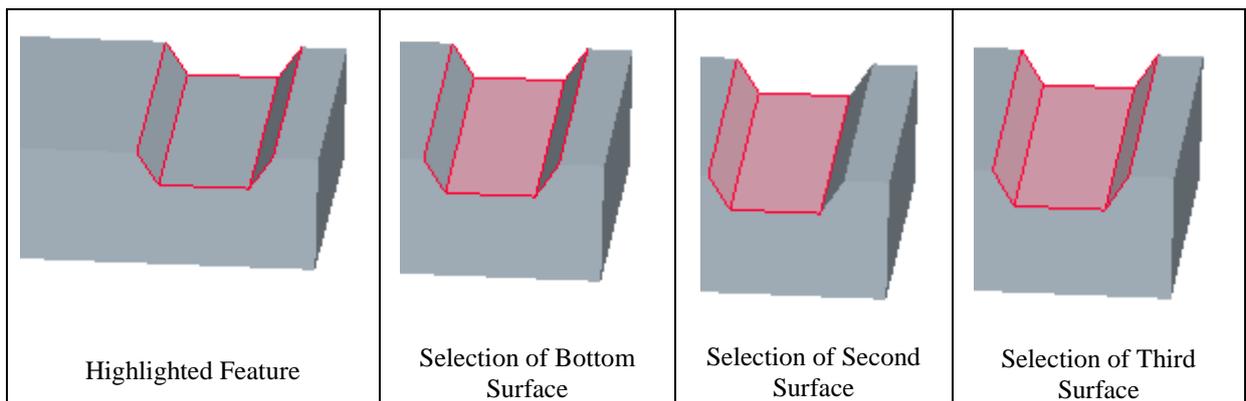


Figure 5.8: Process of Surface selection from Machining Feature

On selection, if the option is not a surface then the option is discarded and if it is the surface then data of the surface is extracted by the API program. The data for the three surface of the slot in Figure 5.7(a) are shown in Table 5.16, Table 5.17, and Table 5.18.

Table 5.16: Bottom Surface

Bottom Surface		
<i>Parameter</i>	<i>Value</i>	
Geometry item	SURFACE	
Id	620	
Surface extremes (min) X, Y, Z	-125.00, -80.00, 35.72	
Surface extremes (max) X, Y, Z	125.00, -120.00, 35.72	
Orient	-1	
Type	Plane	
Vector	Along U	e1 (0.00000, -1.00000, 0.00000)
	Along V	e2 (-1.00000, 0.00000, 0.00000)
	Surface Normal	e3 (0.00000, 0.00000, -1.00000)

Table 5.17: Second Surface

Second Surface		
<i>Parameter</i>	<i>Value</i>	
Geometry item	SURFACE	
Id	622	
Surface extremes (min) X, Y, Z	-125.00, -120.00, 35.72	
Surface extremes (max) X, Y, Z	125.00, -130.00, 50.00	
Orient	-1	
Type	Plane	
Vector	Along U	e1 (0.00000, -0.57358, 0.81915)
	Along V	e2 (-1.00000, 0.00000, 0.00000)
	Surface Normal	e3 (0.00000, -0.81915, -0.57358)

Table 5.18: Third Surface

Third Surface		
<i>Parameter</i>	<i>Value</i>	
Geometry item	SURFACE	
Id	618	
Surface extremes (min) X, Y, Z	-125.00, -80.00, 35.72	
Surface extremes (max) X, Y, Z	125.00, -70.00, 50.00	
Orient	-1	
Type	Plane	
Vector	Along U	e1 (0.00000, -0.57358, -0.81915)
	Along V	e2 (-1.00000, 0.00000, 0.00000)
	Surface Normal	e3 (0.00000, 0.81915, -0.57358)

The extracted details of each surface are written into the database by the software in a structured way so that the data can be read or queried. The Figure 5.9 shows the structured format of the required surface data details which are ready for any query. The data consist of surface normal vector, its orient direction along the axis, surface id and maximum and minimum limit of the surface.

Feat	e31	e32	e33	Orient	Xmin	Xmax	Ymin	Ymax	Zmin	Zmax	id	
Slot		0	0	-1	-1	-125	125	-120	-80	35.72	35.72	620
		0	0.81915	-0.57358	-1	-125	125	-80	-70	35.72	50	618
		0	-0.81915	-0.57358	-1	-125	125	-120	-130	35.72	50	622

Figure 5.9: Entity Details of the Surface in database

5.6.3 Invoked Pro/TOOLKIT functions on selection of Submenu

On selection of submenu to identify a machining feature, a continues chain of functions are called in response to a) identify the design feature as machining features, b) highlight the identified machining feature and c) prompt user to select surfaces of the machining feature.

Consider the model in Figure 5.10(a) and its design feature Figure 5.10(b). The component consists of single Slot Feature when user select the option to identify the slot feature from the menu, the command triggers a chain of functions in sequence. The first function called in the sequence for the selected option would be a user created function called “MenuSlotFunc()”. Each menu option has a unique function created in the API application to be triggered.

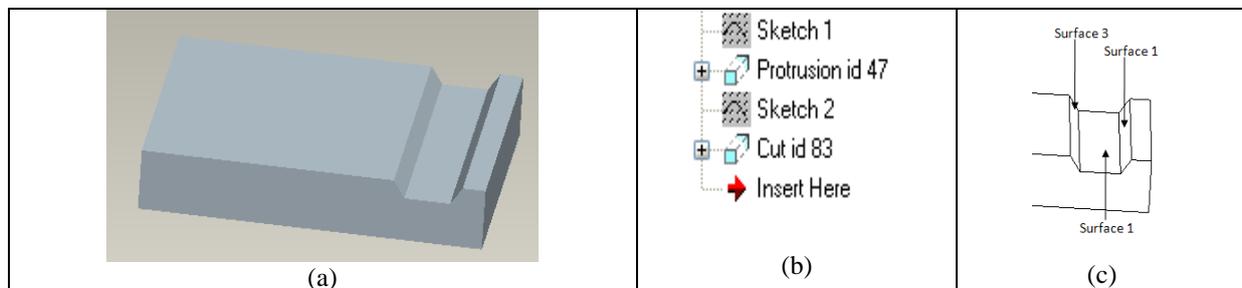


Figure 5.10: Component with Slot Feature

“MenuSlotFunc()” in turn will invoke the next function called “SlotFunc()”, which is stored in the file called “slot.c”. The “SlotFunc()” and “slot.c” is a part of created API application software. “SlotFunc()” will then call the Pro/TOOLKIT functions “ProMdlCurrentGet()” to identify the model in the current section of Pro Engineer. Output of the “ProMdlCurrentGet()” would be a model identification number (mdl_id) which would be used to for the next function called “UserFeatureVisit()”. The model identification number (mdl_id) is passed on

to a function called “UserFeatureVisit()” which collects the data’s consisting of the design features as arrays or data structures used for creation of model. Data structures for the model shown in Figure 5.10(a) would consist of i) Protrusion id47 and ii) Cut id83 as shown in Figure 5.10(b) which makes up the model. The collected data structures are passed on to the next function called “UserRibFind1()” created as part of API software would identifies only the design instance cut. The cut instance is passed to the next function of Pro/TOOLKIT called “ProUtilCollectFeatureGeomItem()”, which collects various geometric features which create the design instance. From the collected geometric features, surfaces are identified which can be a plane or cylindrical surface. The identified surfaces of the design instance cut are checked to ensure the instance is only made up of three surfaces. If the instance is not made of three surfaces then the instance is not a slot feature and is omitted. The cut instance id83 for the Figure 5.10(a) consist of three plane surface as shown in Figure 5.10(c) which confirms to form the slot feature.

Table 5.19: Pro/TOOLKIT Functions for Highlight

Function	Pro/TOOLKIT or Create API software Functions	Input of Fn	Output of Fn
MenuSlotFunc()	Created API fn	-	Call SlotFunc()
SlotFunc()	Created API fn	-	Call ProMdlCurrentGet()
ProMdlCurrentGet()	Pro/TOOLKIT fn	-	Mdl_id
UserFeatureVisit()	Pro/TOOLKIT fn	Mdl_id	Design Instance as (array)
UserRibFind1()	Created API fn	Array of design instance	Cut instance
ProUtilCollectFeatureGeomItem()	Pro/TOOLKIT fn	Cut instance	Surfaces of Cut instance
ProSelectionHighlight()	Pro/TOOLKIT fn	Surface of Cut instance	Highlight the edges of cut instance surfaces and call UserVist1() fn

Once the feature confirms the requirement as machining feature of slot, edges of the surface which forms the features is highlighted using the function “ProSelectionHighlight()” by passing the surface details of the instance. The Table 5.19 represents all the function’s input and output that are used to highlight the edges of surface which create a slot feature.

Parameter of each feature is identified through surfaces which form them. The process of selection of surface is done manually to avoid any confliction which might arise due to

intersecting of surface. The process of selection is done from the bottom surface or the surface that orientates the feature followed by side surface which forms the wall. Once the surface edges are highlighted, function “UsrVist1()” is called. The “UsrVist1()” is created as part of API software, the function calls “ProMdlCurrentGet()” to get the current model in the session. The model details is passed on to the next function called “ProTestGeomShape()” and the function “ProSelect()” is also called to request the user to input a selection. The input selection is cross checked with the current model in session. The selection is passed on to a function ProUtilGeomItemDump() which identifies the selection, if the selected option is surface then ProSurfaceInit() confirms the surface as part of the model and then ProSurfaceToGeomitem() identifies the geometric details that forms the surface like the vertex and edges. Using the geometry details of the surface a) surface extremes are calculates using the function ProSurfaceExtremes() and stored in array, b) the surface details is passed on to ProSurfaceGeoItemShapeDump() and then to ProUtilSurfacedataPrint() which consist of ProPlanedataGet() and ProCylinderdataGet() which collects vector and its data are collected. Table 5.20 represents all the function that are used to collect the data of the selected surface which were highlighted.

The data collected by the function are written on to a dump file using the software itself. The dumped data is a flat file database that is saved as a structured data format in excel. The database is saved as structured format so that the data can be accessed for reading and querying.

Table 5.20: Pro/TOOLKIT function for Data

Function	Pro/TOOLKIT or Create API software Functions	Input of Fn	Output of Fn
UserVist1 ()	Created API fn	-	Call ProMdlCurrentGet()
ProMdlCurrentGet()	Pro/TOOLKIT fn	-	Model type and Call ProUtilGeomItemDump()
ProUtilGeomItemDump()	Pro/TOOLKIT fn	ProMdl	Call ProSelect()
ProSelect()	Pro/TOOLKIT fn	-	Selection
ProSurfaceInit ()	Pro/TOOLKIT fn	Selection, ProMdl,	Checked both are same
ProSurfaceToGeomitem ()	Pro/TOOLKIT fn	Surface, ProMdl	Geometry of surface,
ProSurfaceExtremesEval()	Pro/TOOLKIT fn	Surface	Extremes of surfaces are calculated
ProUtilSurfacedataPrint ()	Pro/TOOLKIT fn	Surface	Data of surface – Type, orient is collected
ProPlanedataGet ()	Pro/TOOLKIT fn	Surface	Dep. on surface type vector is found
ProCylinderdataGet()	Pro/TOOLKIT fn	Surface	Dep. on surface type vector is found

5.7 Identifying Number of Setup and Range

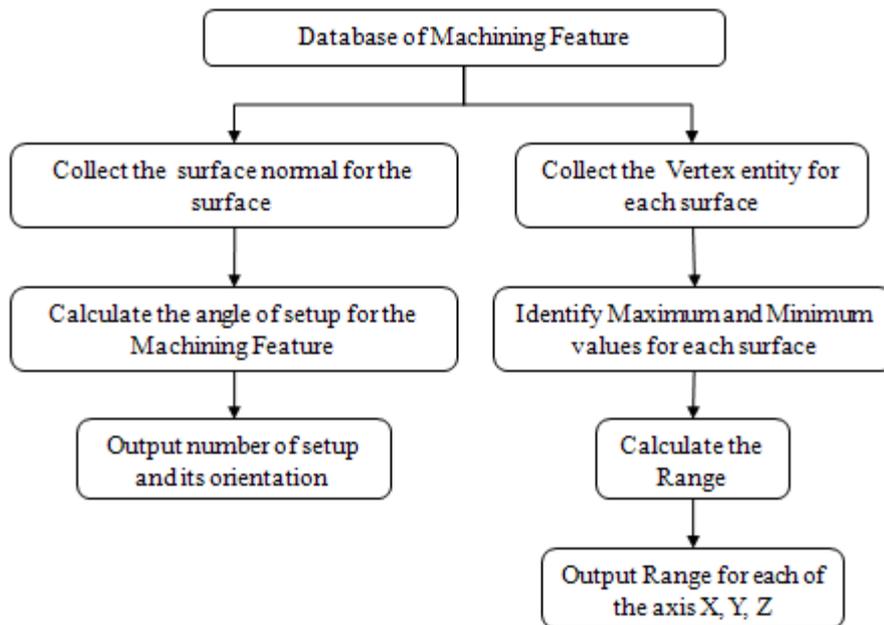


Figure 5.11: Process Flow of VB program

A software using visual basic (VB) program was created that would a) read and query the data populated in the database by the API software, b) analyses the number of setup and c) identify the range of the machining. VB Program would query the database twice, first instance to identify the number of setup and second for the range of the machining. The process flow diagram in Figure 5.11 shows the working of VB software.

The first query would request for surface normal vector details of all the surfaces which orients the machining feature that would consist details from the bottom surface or the surface which is selected first during selection of surfaces. Using normal vector, orientation of the surface is identified using VB software. The identified orientation is stored in two clusters a) along positive and negative traverse axis of X, Y, Z and b) along rotation axis a, b, c. Created VB software would further store the machining feature id and count the number of setup needed for the machining. Figure 5.12 shows the part of the VB program that shows the number of setup and its orientation along the axis.

Number of Machining Features: 0

Along X: + [dropdown], - [dropdown]

Along Y: + [dropdown], - [dropdown]

Along Z: + [dropdown], - [dropdown]

Along a: [dropdown]

Along b: [dropdown]

Along c: [dropdown]

Number of Machining Setup for 3 Axis: 0

Figure 5.12: Identified Machining Setups using VB Program

Axis	Min	Max	Range	Rotational Angle along
X	[input]	[input]	[input: 0]	a [dropdown: 0]
Y	[input]	[input]	[input: 0]	b [dropdown: 0]
Z	[input]	[input]	[input: 0]	c [dropdown: 0]

Figure 5.13: Identified Range for Machining using VB Program

Second query scan across all the records of the entire surfaces in the database and identify the maximum and minimum values along X, Y and Z axis. Range of individual axis is calculated which would be used to identify the maximum and minimum limits in which identified

machining feature can be machined. Figure 5.13 shows the part of VB program that represents the limits of machining.

5.8 User Input for Machining Feature Sub-System

Machining feature's orientation and range was identified in the previous section 5.7, which are not sufficient for machining. Further details are necessary like a) cutting tools, b) accuracy, b) repeatability, d) spindle detail's, e) feed rate f) any addition axis and e) coolant & removal system. The need for these features in any machining process is discussed in detail in section 4.2. In addition details like control type and fixture requirements are also considered. Controllers are necessary to eliminate the user interface so that various machining parameter can be control and interconnect to work concurrently. Controllers at present in machine tools are available in diverse forms from the manufacture or by the complexity to handle number of axis as discussed in section 2.6.

The screenshot shows a VB form titled "Enter Machine tool details for Selection". The form contains the following fields and controls:

- Enter Spindle Speed in rpm: 5000
- Number of Spindle Head: 1
- Enter Fee Rate in m/min: 24
- Enter Number of Tool Carosel: Auto (dropdown), 20
- Enter Number of Pallet Changer: Auto (dropdown), 20
- Enter Repeatability in microns: 1
- Enter Accuracy for Machining in microns: 3
- Enter Rotational for Axis: a 0, b 0, c 0
- Reset Rotational Axis: button
- Select Fixture: STANDARD (dropdown)
- Select Controller: SIEMENS (dropdown)
- Coolant System: P (dropdown)
- Removal System Dust: P (dropdown), Swarf A (dropdown)

Figure 5.14: VB form to collect sub-system feature of machining feature

Fixture plays a vital part in the machining as these are important to hold the machining component rigidly and align them to the cutting tool. Some of the common fixtures are standard accessories available in machine tools, need for any special feature is also

considered if required for machining. These sub-system details were not automated, as there can be numerous combinations possible. Instead the details are requested from the user in the VB form as input shown in Figure 5.14.

The form is a simple user interface system where the details like a) spindle speed, b) number of spindle head, c) feed rate, d) number of tool carousel, e) repeatability and f) accuracy are entered. Type of tool change, controller and fixture and pre-defined in combo box option were user selection is request. Additional rotational axis option is included to reduce the machining setup as check box and rotational angle is request in the text box. It also makes sure that user cannot select more than two axes of rotation as three axes rotation is not possible neither available. These sub-feature details are incorporated with the capacity details in the same form created using VB programming. All the various factors identified and requested from the user form the alphanumeric string for the machining component. The representation of these alphanumeric string forms the alphanumeric code of the machining component.

5.9 Generation of Alphanumeric code for Machining Component

Axis	Min	Max	Range	Rotational Angle along	
X	-150	150	300	a	0
Y	-100	100	200	b	300
Z	-50	50	100	c	0

Number of Machining Features **4**

Along X + - Along a

Along Y + - Along b

Along Z + - Along c

Number of Machining Setup for 3 Axis **2**

Figure 5.15: Identified Alphanumeric Strings for the component in Figure 5.3

Alphanumeric code of Machining Component is created, using the alphanumeric string identified in section 4.8. Consider the model in Figure 5.3 the alphanumeric string identified using the API program as shown in Figure 5.15 would gives us the number of setup,

machining range. Figure 5.16 shows the requested inputs for machining the component from the user to create the alphanumeric string.

Figure 5.16: User input for Machining the Component in Figure 5.3

Alphanumeric string from the program and the user inputs are used to create the alphanumeric code for the component in Figure 5.3 is shown in Table 5.21.

Table 5.21: Alphanumeric Code of the component in Figure 5.3

03:	01:	03:	MP01:	AT20:	30-1S90:	STAN:	FANU:	X300:	Y200:	Z100:	B300:	PFF
No. of Axis	Repeatability	Accuracy	Pallet changer	Cutting tool	Spindle details	Fixture	Controller	X traverse	Y traverse	Column and Z traverse	b axis rotation	Sub system Coolant, Swarf, Dust

5.10 Marrying of Alphanumeric Codes of Machine Tool Feature and Machining Component Feature.

Alphanumeric code generate for the machining component set down the basis for selecting a machine tool. The alphanumeric code defines the parameters set for machining the component; these parameter values are extracted from the Component's Alphanumeric code and used for selection of machine tool.

Chapter 6: Case Study

6.0 Introduction

The component in Figure 6.1 selected for the case study is exhibit model from MACH-2008 for a mill-turn machine tool. Preparation of model is done using Pro Engineer by material removal instance only. Suitable raw stock is first cut from a block of material, and then cuts are created to produce the component in CAD. The prepared model is analyzed using the developed API software to extract the component details. The extracted details are further stored and read from a database using the created VB software. The software also identifies the setups and capacity further generates the alphanumeric code for the component. The generated alphanumeric code of the component is segregated and matched to the machine tool features from the created database of machine tools. The matched machine tools are listed in the software for selection by the user for machining. The optimal choice of machine tool for the component is further discussed.

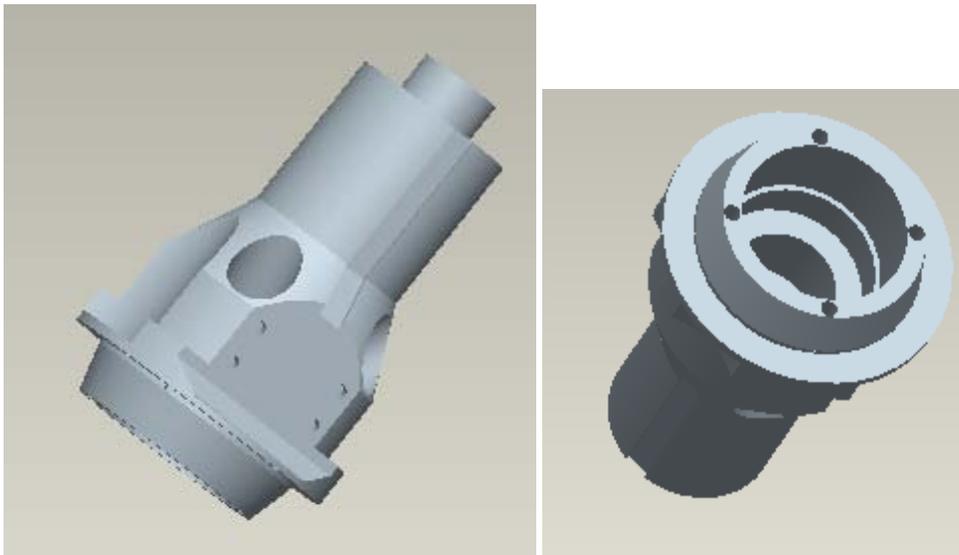


Figure 6.1: Case Study Component

6.1 Preparation of the Model

A rectangular block of material which fits the component shown in Figure 6.1 is first created as shown in Figure 6.2(a) and further the block is trimmed using three cut as shown in Figure

6.2(b). The Table 6.1 shows the various cuts that were used to model the component in Pro Engineer including the feature tree.

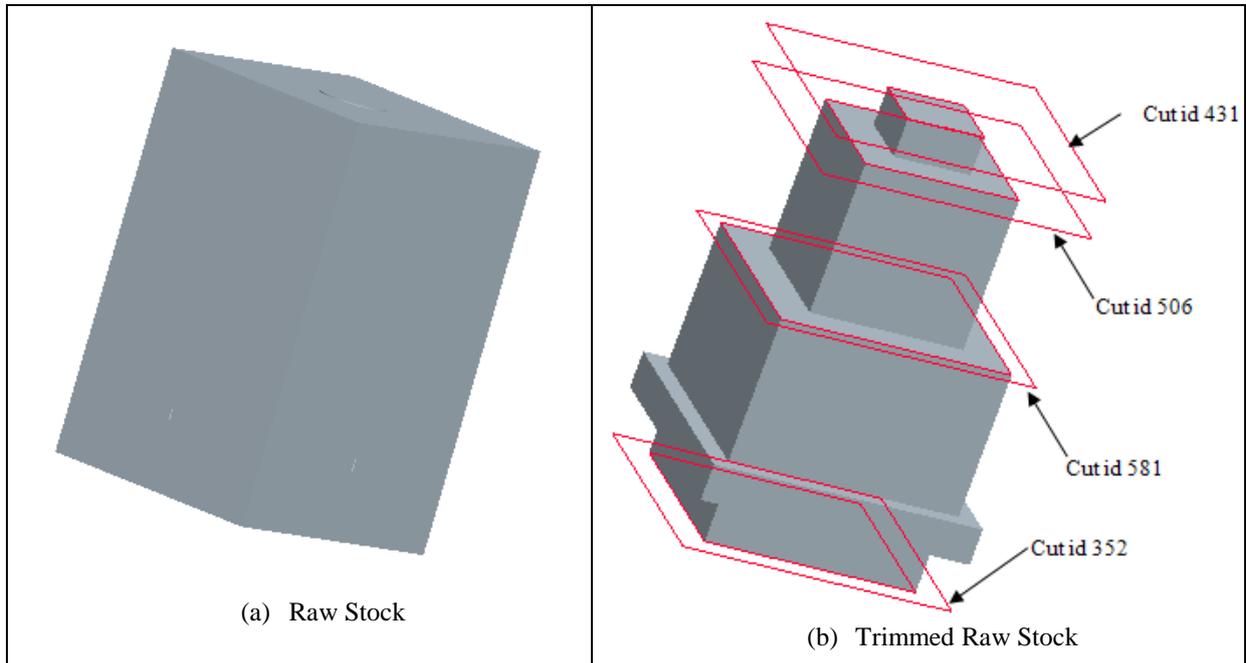
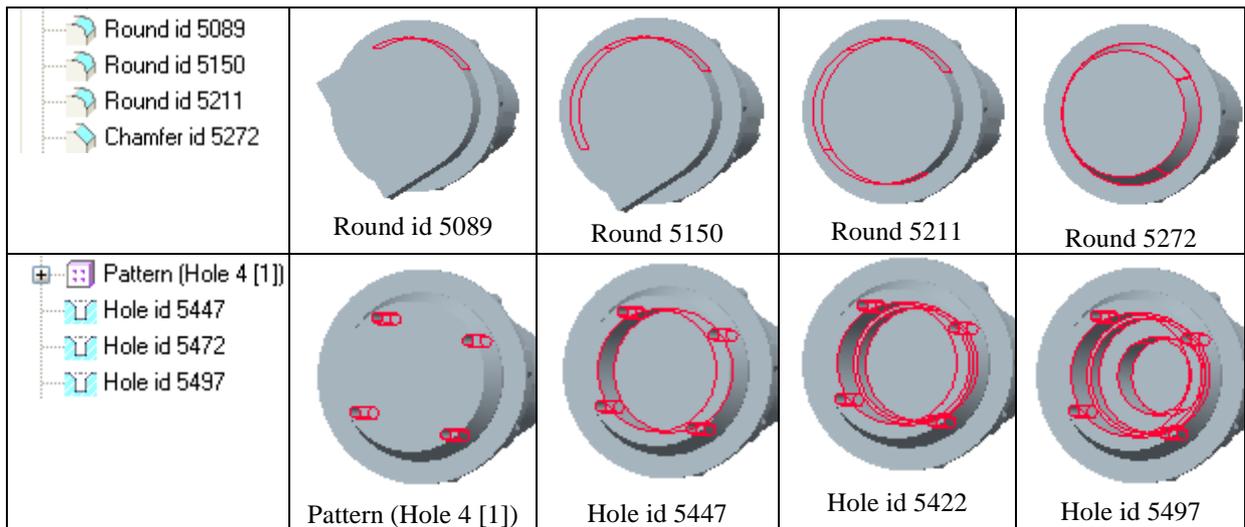


Figure 6.2: Raw Stock for the component and trimming

Table 6.1: Creation of the model using cut instance

Feature Tree	Cut Instance			
<ul style="list-style-type: none"> Round id 2791 Round id 2833 Round id 2875 Round id 2917 				
	Round id 2791	Round id 2833	Round id 2875	Round id 2917
<ul style="list-style-type: none"> Round id 2959 Round id 3001 Round id 3043 Round id 3085 				
	Round id 2959	Round id 3001	Round id 3043	Round id 3085
<ul style="list-style-type: none"> Round id 3127 Round id 3169 Round id 3211 Round id 3253 				

	Round id 3127	Round id 3169	Round id 3211	Round id 3235
<ul style="list-style-type: none"> Round id 3295 Round id 3348 Round id 3401 Round id 3454 				
<ul style="list-style-type: none"> Chamfer id 3711 Cut id 3785 Cut id 3831 Cut id 3877 				
<ul style="list-style-type: none"> Cut id 3908 Cut id 3951 Cut id 4049 Curve id 4100 Cut id 4106 				
<ul style="list-style-type: none"> Chamfer id 4135 Cut id 4194 Curve id 4260 Cut id 4270 Mirror id 4346 Mirror id 4402 				
<ul style="list-style-type: none"> Pattern (Hole 1 [1]) Pattern (Hole 2 [1]) Pattern (Hole 3 [1]) Round id 5028 				



6.2 Extraction from the Component

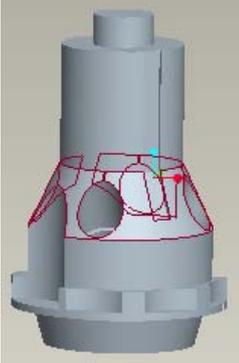
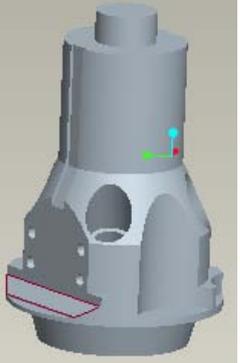


Figure 6.3: Sub menu created by API software

Using the developed API software, a menu option is created along side of the main menu in Pro Engineer. The option provides a list of sub menu as shown in Figure 6.3, for the user to select an option to identify various machining feature.

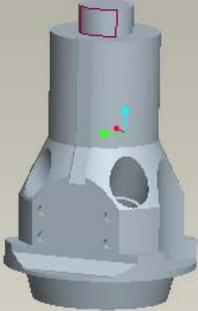
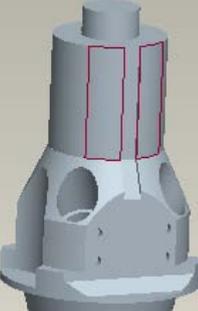
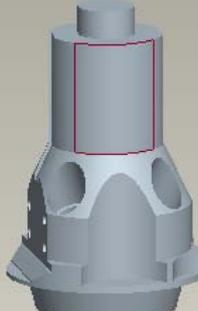
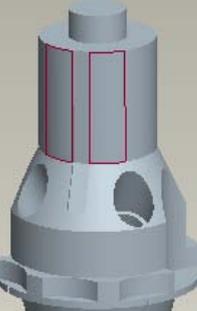
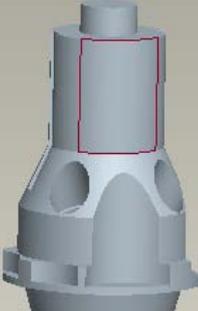
On Selection of a particular machining feature, the software identifies and highlights machining feature's edges from the model and further prompts the user to select the surfaces highlighted by the edges. On selection of the menu "Idy Chamfer Features" the chamfer features in the model are highlighted one after the other as shown in Table 6.2.

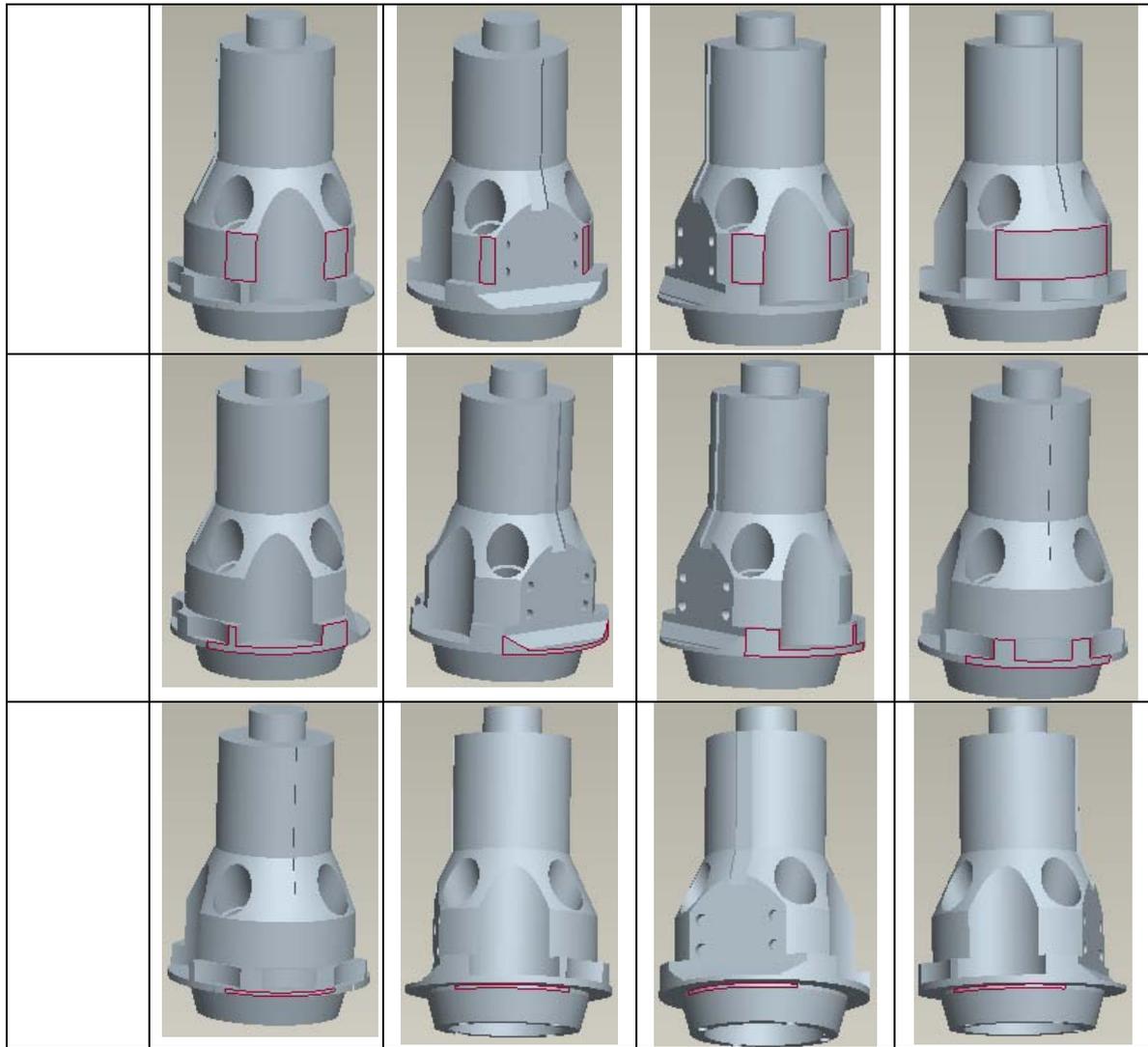
Table 6.2: Idy Chamfer Menu

Sub menu	Identified Chamfer Features from the model		
Idy Chamfer Features			

On selection of menu “Idy Round Feature” the following round feature in the model are highlighted as in Table 6.3.

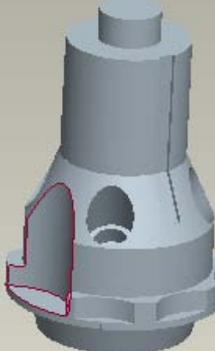
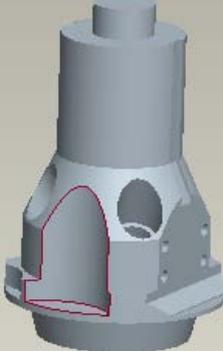
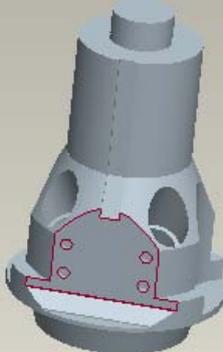
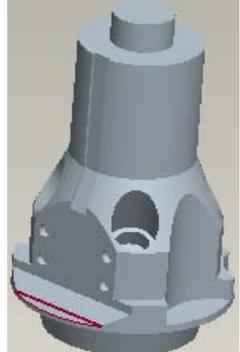
Table 6.3: Idy Round Menu

Sub menu	Identified Round Features from the model			
Idy Round Features				
				



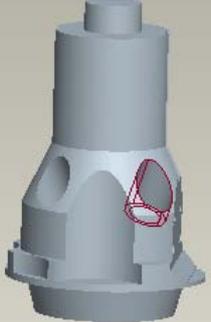
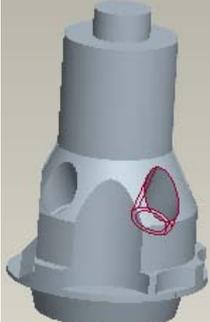
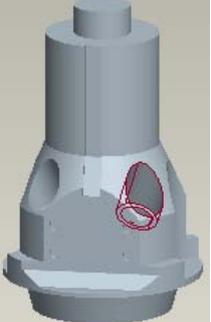
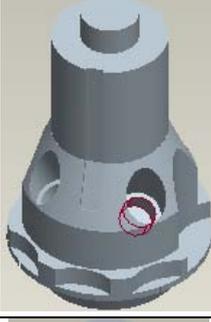
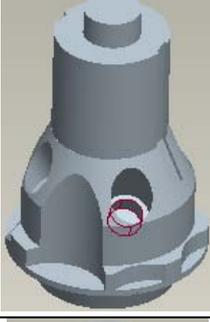
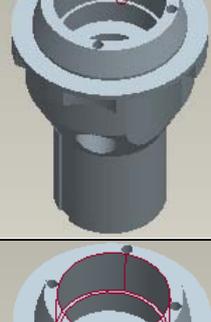
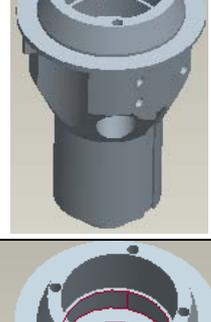
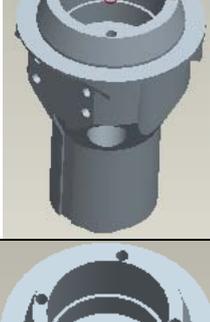
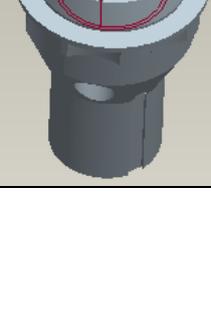
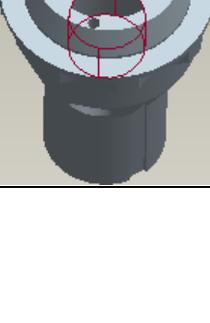
On selection of menu “Idy Step Feature” the following step feature in the model are highlighted as in Table 6.4.

Table 6.4: Idy Step Menu

Sub menu	Identified Step Features from the model			
Idy Step Features				
				

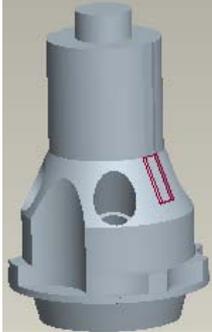
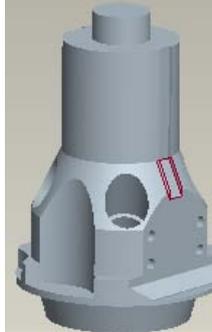
On selection of menu “Idy Hole Feature” the following hole feature in the model are highlighted as in Table 6.5.

Table 6.5: Idy Hole Menu

Sub menu	Identified Round Features from the model			
Idy Hole Features				
				
				
				
				

On selection of menu “Idy Pocket Feature” the following pocket feature in the model are highlighted as in Table 6.6.

Table 6.6: Idy Pocket Menu

Sub menu	Identified Pocket Features from the model			
Idy Pocket Features				

The surface details of each surface with their normal vector are grouped with respect to machining feature and tabulated in Table 6.7.

Table 6.7: Data for all the identified machining features

Machining Features	Direction Cosine			Orient	Xmin	Xmax	Ymin	Ymax	Zmin	Zmax	id
Chamfer	0	0	-1	1	0.5	28.47	60	28.47	-22.78	20	3721
	0	0	-1	1	-60	-0.5	0.5	40.05	-22.78	20	3712
	0	0	-1	1	-22.06	-40.05	-55.96	-0.5	-22.78	20	3737
	0	0	-1	1	0.5	40.05	-60	-0.5	-22.78	20	3729
Chamfer	-0.47315	0.47315	0.74314	1	-69.99	-1.42	1.42	69.99	-62	-62	4136
Chamfer	0	0	1	1	0.5	39.04	49	39.04	-100	-77.61	5273
	0	0	1	1	0.5	55	-49	-0.5	-100	-77.61	5298
	0	0	1	1	-34.79	-55	-34.8	-0.5	-100	-77.61	5290
	0	0	1	1	-49	-0.5	0.5	55	-100	-77.61	5282
Round	0	0	1	1	-20	-0.05	0.05	20	100	120	2792
Round	0	0	1	1	-14.16	-20	-14.16	-0.05	100	120	2834
Round	0	0	1	1	0.05	20	-20	-0.05	100	120	2876
Round	0	0	1	1	0.05	14.16	20	14.16	100	120	2918
Round	0	0	1	1	-40	-0.5	0.5	40	20	100	2960
Round	0	0	1	1	-25.89	-40	-30.76	-0.5	20	100	3002
Round	0	0	1	1	0.5	40	-40	-0.5	20	100	3044
Round	0	0	1	1	0.5	30.76	40	25.89	20	100	3086
Round	0	0	1	1	60	55.96	0.5	22.06	-56	-22.78	3128
Round	0	0	1	1	-60	-0.5	0.5	60	-56	-22.78	3170
Round	0	0	1	1	-55.96	-60	-22.06	-0.5	-56	-22.78	3212
Round	0	0	1	1	0.5	60	-60	-0.5	-56	-22.78	3254

Round	0	0	-1	1	70	66.27	0.5	22.96	-75	-56	3296
Round	0	0	-1	1	-70	-0.5	0.5	70	-75	-62	3349
Round	0	0	-1	1	-49.64	-70	-49.65	-0.5	-75	-56	3402
Round	0	0	-1	1	0.5	70	-70	-0.5	-75	-70	3455
Round	0	0	-1	1	0.5	55	-55	-0.5	-77.61	-75	5029
Round	0	0	-1	1	-39.04	-55	-39.04	-0.5	-77.61	-75	5090
Round	0	0	-1	1	-55	-0.5	0.5	55	-77.61	-75	5151
Round	0	0	-1	1	0.5	39.04	55	39.04	-77.61	-75	5212
Step	0	0	1	1	-49.64	-30.3	-49.64	-35	-70	-70	3788
	0	0	1	-1	-22.96	-31.88	-66.27	-33.23	-70	7.58	3794
Step	0	0	1	1	30.3	49.64	35	49.64	-70	-70	3834
	0	0	1	-1	30.3	31.88	35	33.23	-70	7.58	3840
Step	0	0	1	1	33.79	61.51	-61.51	-33.79	-70	-70	3880
	0	0	1	-1	33.79	61.51	-61.51	-33.79	-70	-56	3888
Step	0	0	1	1	-17.67	20.44	-67.85	-67.08	-70	-70	3911
	0	0	1	-1	-17.67	20.44	-67.85	-67.08	-70	-56	3917
Step	0	0	1	1	67.08	67.85	-20.44	17.67	-70	-70	3954
	0	0	1	-1	67.08	67.85	-20.44	17.67	-70	-56	3962
Step	0	0	1	1	-70	0	0	70	-62	-62	4052
	0.70711	-0.70711	0	-1	-70	-10.92	0	59.08	-62	-22.78	4058
Step	0	0	1	1	-67.83	-17.72	17.72	67.83	-72	-72	4112
	0.70711	-0.70711	0	-1	-67.83	-17.72	17.72	67.83	-72	-71	4117
Hole	0	-0.42262	-0.9063	-1	-14.03	14.03	36.16	45.8	-23.45	-27.94	4475
	0	-0.42262	-0.9063	-1	0	11.61	27.39	45.25	-19.36	5.93	4478
	0	-0.42262	-0.9063	-1	-14.03	0	36.16	42.89	-23.45	13.9	4480
Hole	-0.42262	0	-0.9063	-1	36.16	45.8	-14.03	14.03	-23.45	-27.94	4511
	-0.42262	0	-0.9063	-1	27.39	44.65	0	10.37	-19.36	7.81	4516
	-0.42262	0	-0.9063	-1	36.16	42.89	-14.03	0	-23.45	13.9	4514
Hole	0	0.42262	-0.90631	-1	-9.95	9.95	-51.16	-30.81	-30.44	-20.95	4543
	0	0.42262	-0.9063	-1	0	8.07	-54.58	-43.87	-32.03	10.41	4548
	0	0.42262	-0.9063	-1	-9.95	0	-51.16	-42.89	-30.44	13.9	4546
Hole	0.42262	0	-0.9063	-1	-51.16	-30.81	-9.95	9.95	-30.44	-20.95	4575
	0.42262	0	-0.9063	-1	-54.58	-43.71	0	7.45	-32.03	10.96	4578
	0.42262	0	-0.9063	-1	-51.16	-42.89	-9.95	0	-30.44	13.9	4580
Hole	0	-0.42262	-0.9063	-1	-9.96	9.96	30.72	41.14	-34.15	-39.01	4608
	0	-0.42262	-0.9063	-1	0	10.75	25.51	44.7	-31.72	-27.43	4611
	0	-0.42262	-0.9063	-1	-9.96	0	30.72	51.42	-34.15	-30.56	4613
Hole	-0.42262	0	-0.9063	-1	30.72	41.14	-9.96	9.96	-34.15	-39.01	4783
	-0.42262	0	-0.9063	-1	30.72	51.42	-9.96	0	-34.15	-30.56	4786
	-0.42262	0	-0.9063	-1	25.51	44.7	0	10.75	-31.72	-27.43	4788
Hole	0	0.42262	-0.9063	-1	-5.75	5.75	-44.95	-26.9	-40.79	-32.37	4807
	0	0.42262	-0.9063	-1	-5.75	0	-44.95	-30.58	-40.79	-20.84	4810

	0	0.42262	-0.9063	-1	0	7.63	-46.35	-33.2	-41.44	-22.07	4812
Hole	0.42262	0	-0.9063	-1	-44.95	-26.9	-5.75	5.75	-40.79	-32.37	4831
	0.42262	0	-0.9063	-1	-46.35	-33.2	0	7.63	-41.44	-22.07	4834
	0.42262	0	-0.9063	-1	-44.95	-30.58	-5.75	0	-40.79	-20.84	4836
Hole	0.70711	-0.70711	0	-1	-15.67	-11.34	48.03	52.36	-51.57	-46.43	4860
	0.70711	-0.70711	0	-1	-18.94	-13.83	51.06	56.17	-51.35	-49	4865
	0.70711	-0.70711	0	-1	-19.48	-14.37	50.52	55.63	-49	-46.65	4863
Hole	0.70711	-0.70711	0	-1	-15.67	-11.34	48.03	52.36	-31.57	-26.43	4888
	0.70711	-0.70711	0	-1	-18.94	-13.83	51.06	56.17	-31.35	-29	4893
	0.70711	-0.70711	0	-1	-19.48	-14.37	50.52	55.63	-29	-26.65	4891
Hole	0.70711	-0.70711	0	-1	-52.44	-48.11	11.26	15.59	-51.57	-46.43	4918
	0.70711	-0.70711	0	-1	-55.71	-50.6	14.29	19.4	-51.35	-49	4923
	0.70711	-0.70711	0	-1	-56.25	-51.14	13.75	18.86	-49	-46.65	4921
Hole	0.70711	-0.70711	0	-1	-52.44	-48.11	11.26	15.59	-31.57	-26.43	4942
	0.70711	-0.70711	0	-1	-55.71	-50.6	14.29	19.4	-31.35	-29	4947
	0.70711	-0.70711	0	-1	-56.25	-51.14	13.75	18.86	-29	-26.65	4945
Hole	0	0	1	-1	-3.06	3.06	41.93	47.07	-55	-55	5351
	0	0	1	-1	-4	3.06	44.5	47.07	-100	-55	5354
	0	0	1	-1	-3.24	4	42.15	44.5	-100	-55	5356
Hole	0	0	1	-1	41.93	47.07	-3.06	3.06	-55	-55	5379
	0	0	1	-1	44.5	47.07	-4	3.06	-100	-55	5382
	0	0	1	-1	41.26	44.5	-2.35	4	-100	-55	5384
Hole	0	0	1	-1	-3.06	3.06	-47.07	-41.93	-55	-55	5403
	0	0	1	-1	-4	3.06	-44.5	-41.93	-100	-55	5408
	0	0	1	-1	-3.24	4	-46.85	-44.5	-100	-55	5406
Hole	0	0	1	-1	-47.07	-41.93	-3.06	3.06	-55	-55	5427
	0	0	1	-1	-47.74	-44.5	-2.35	4	-100	-55	5430
	0	0	1	-1	-44.5	-41.93	-4	3.06	-100	-55	5432
Hole	0	0	1	-1	-28.28	28.28	-28.28	28.28	-60	-60	5452
	0	0	1	-1	-40	28.28	0	28.28	-100	-60	5455
	0	0	1	-1	-29.56	40	-26.95	0	-100	-60	5457
Hole	0	0	1	-1	-26.52	26.52	-26.52	26.52	-40	-40	5477
	0	0	1	-1	-37.5	26.52	0	26.52	-60	-40	5480
	0	0	1	-1	-27.71	37.5	-25.26	0	-60	-40	5482
Hole	0	0	1	-1	-19.55	19.55	-15.59	15.59	-5	-5	5502
	0	0	1	-1	-16.73	25	-18.58	0	-40	-5	5507
	0	0	1	-1	-25	19.55	0	15.59	-40	-5	5505
Pocket	0.70711	-0.70711	0	1	22.27	30.76	-30.76	-22.27	19	100	4202
	-0.70711	-0.70711	0	-1	22.27	23.86	-30.76	-32.35	19	100	4209
	0.70711	0.70711	0	-1	30.85	30.76	-22.36	-22.27	19	100	4213
	-0.29884	0.29884	0.90631	-1	22.17	32.5	-31.01	-23.66	19.05	20.04	4283
Pocket	-0.64086	0.64086	-0.42262	-1	32.33	31.01	-41.17	-22.17	-11.76	19.05	4278

	-0.70711	-0.70711	0	-1	32.33	23.66	-41.17	-32.5	-11.76	20.04	4289
	0.29884	-0.29884	-0.90631	-1	32.33	42.76	-41.17	-33.92	-11.76	-10.71	4287
	0.70711	0.70711	0	-1	41.17	32.47	-32.33	-23.63	-11.76	20	4285
Th Pocket	0.70711	-0.70711	0	-1	-30.76	-22.27	22.27	30.76	19	100	4351
	-0.70711	-0.70711	0	1	-22.36	-23.86	30.85	32.35	19	100	4355
	0.70711	0.70711	0	1	-30.85	-30.76	22.36	22.27	19	100	4353
	-0.29884	0.29884	-0.90631	1	-31.01	-23.66	22.17	32.5	19.05	20.04	4408
Th Pocket	-0.64086	0.64086	0.42262	1	-39.42	-22.17	30.58	31.01	-6.46	19.05	4407
	-0.70711	-0.70711	0	1	-30.58	-23.66	39.42	32.5	-6.46	20.02	4409
	0.70711	0.70711	0	1	-39.42	-32.5	30.58	23.66	-6.46	20.04	4411
	-0.29884	0.29884	-0.90631	1	-31.01	-23.66	22.17	32.5	19.05	20.04	4408

6.3 Selection of suitable Machine Tool for the component

Figure 6.4: Software created using Visual Basic

On selection of sub menu option “Select Machine” software created using Visual basic opens for the user to select suitable machine tool for the component. The visual basic software form is shown in Figure 6.4.

Data collected for the component was opened in excel using the button “Open Feature xls” and saved into excel format (structure database). On click of the next button “Load Feature” the software calculates a) range of the machining using minimum and maximum values of X, Y and Z axis b) identifies the number of setup required for three axis machine, c) Number of machining features and d) setup orientations and groups of the machining features with respect to axis orientation as shown in Figure 6.5.

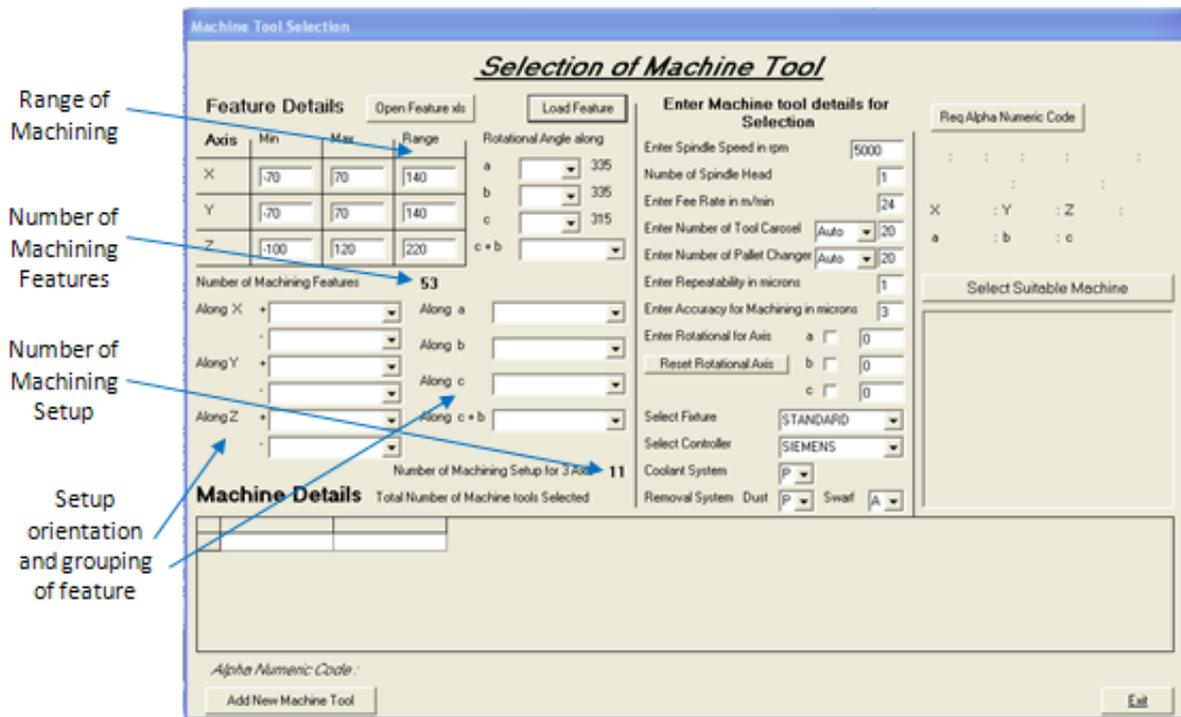


Figure 6.5: Identifying parameter from the data using created software

The range of machining that is required for the component along X, Y, Z are 140, 140, 220 respectively, total number of machining feature identified are 53 which can be machined using 11 setup. The middle section of the form requests user to input details for selection of machine tool like a) cutting parameters, b) accuracy, c) controller and d) fourth and fifth axis options as shown in Figure 6.6. Using the details identified in the first section and input details from the second section, alphanumeric code to machine to the component is generated in the third section which is shown in Figure 6.7. The third section also consists of a button “Select Suitable Machine”, which would select all the suitable machine tool which can machine the component. The selected machine tools are tabulated with their specification as shown in Figure 6.8.

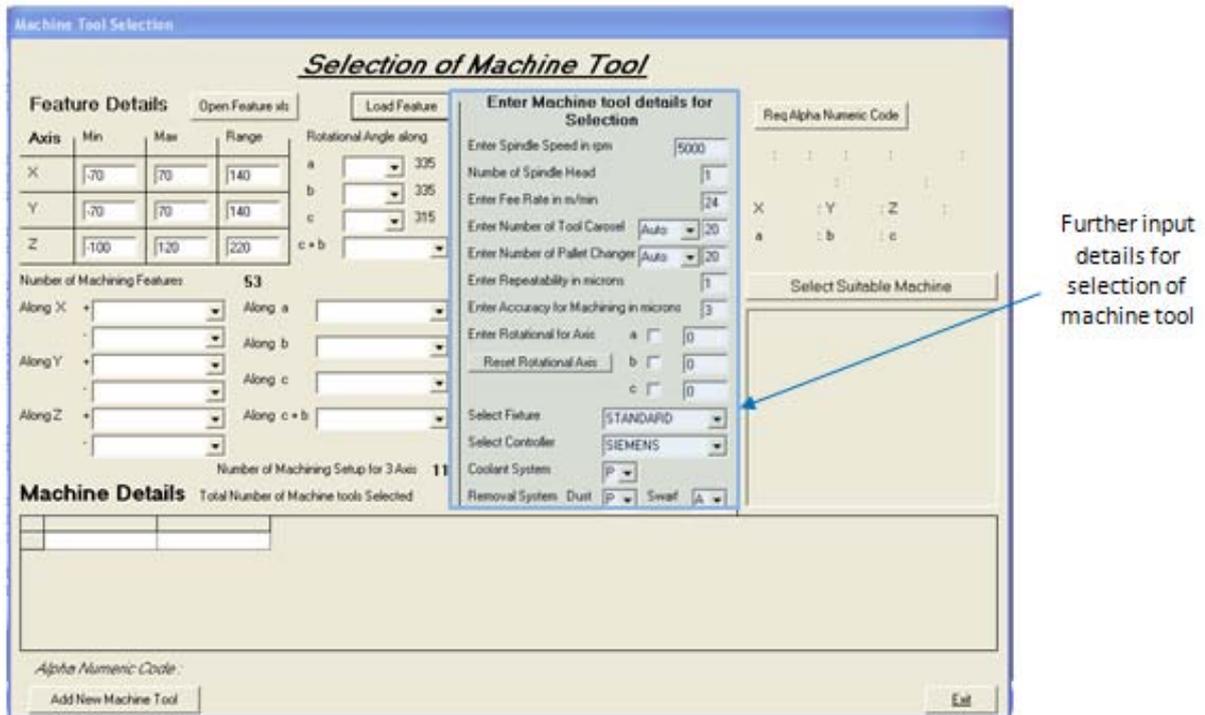


Figure 6.6: Second section to request user to input details for machine tool selection

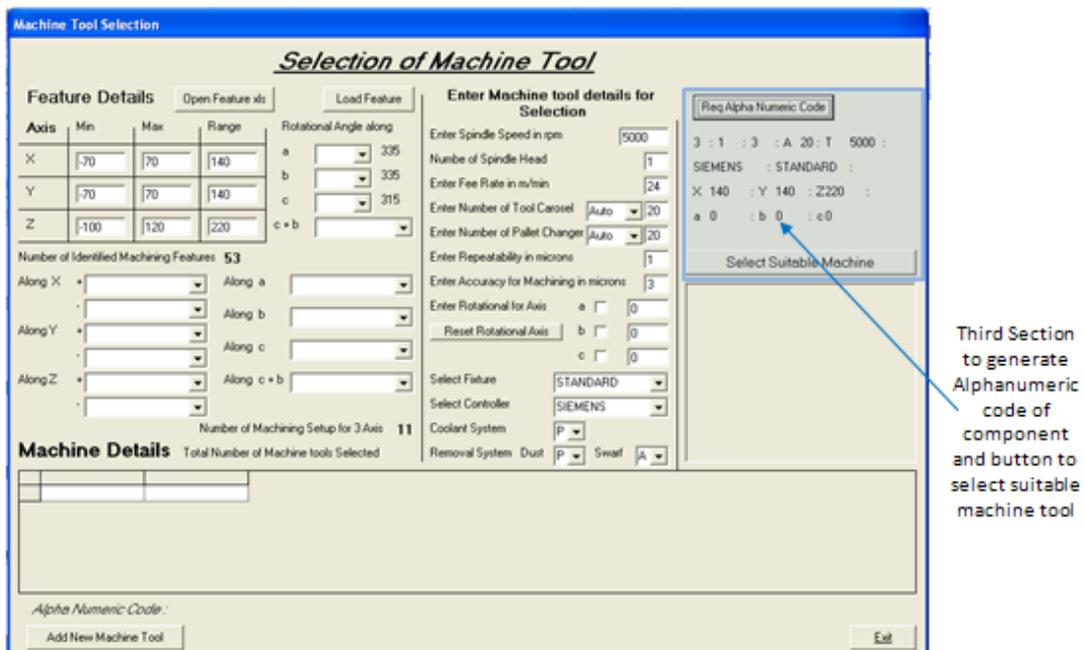


Figure 6.7: Section three of the software created using Visual Basic

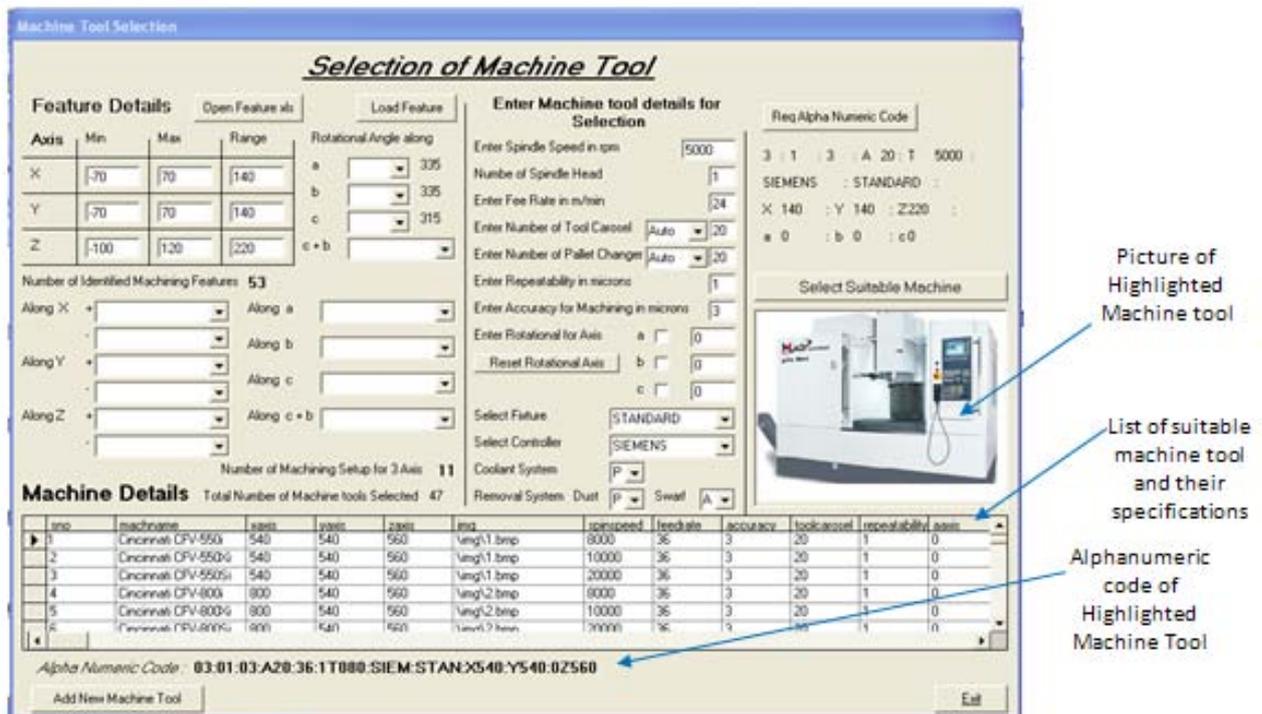


Figure 6.8: List of suitable machine tools selected

6.4 Optimal Choice from Machine tool Database

Selection of the optimal choice of machine tool for the component is really important as the selection process of a machine tool has been a critical issue for companies. Improper selection of a machine tool might cause many problems having a negative effect on productivity, precision, flexibility, and a company's responsive manufacturing capabilities. Present system of selection of machine tool would either use a matrix method [78-81] or a database [82] for selection. Methods [78-81] uses features of machine tool for selection were as the component details are not matched in the selection process. The created software inter-relates the components specification and matches to the machine tools features. This not only benefits a vendor to outsource a component by machining the optimal machine tool, but also reduces the confusion and timing for the selection of machine tool.

6.4.1 Choice of 3-Axis Machine Tool

The component analyzed in the Figure 6.1 for the case study would require up to 11 setups to complete the various machining features on a three traverse axis of a machine tool. The setup would require stopping the machining process, de-clamping the component and res-position the component to a different orientation of machining. The various setups required to

complete the process is identified and populated into combo box of axis as shown in Figure 6.9 and various setup required from initial datum setup are tabulate in the Table 6.8.

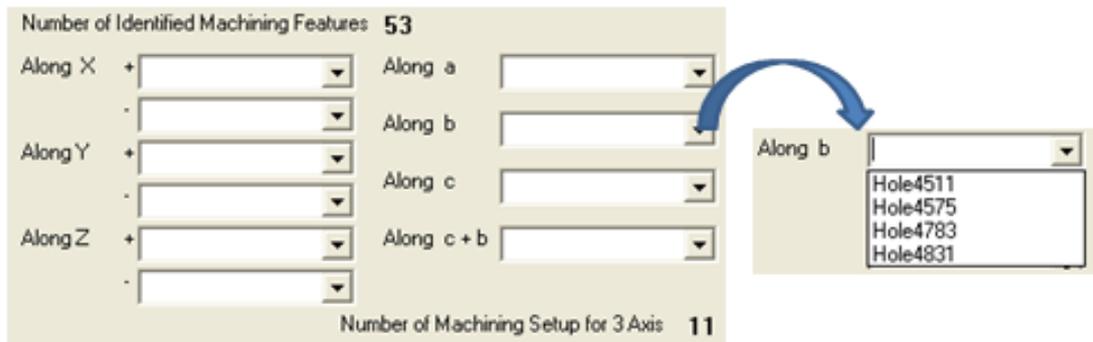


Figure 6.9: Identified Machining Features populated along the axis

Table 6.8: Setup angle and number of Setups

Along Axis	Setups Angle	Number of Setup
+Z	Initial Datum Setup	1st
-Z	YES	2nd
a	25deg, 335deg	3 rd and 4th
b	25deg, 335deg	5 th and 6th
c	135deg, 315deg	7 th and 8th
c + b	135+45deg, 315+45deg, 315+48deg	9 th , 10 th and 11 th

Further with the details entered by the user, optimal choice of machine tool for three axes are selected from the database and populated in a table as shown in Figure 6.10.

sno	machname	xaxis	yaxis	zaxis	img	spinspeed	feedrate	accuracy	toolcarusel	repeatability	aaxis
1	Cincinnati CFV-550i	540	540	560	\\img\1.bmp	8000	36	3	20	1	0
2	Cincinnati CFV-550Ki	540	540	560	\\img\1.bmp	10000	36	3	20	1	0
3	Cincinnati CFV-550Si	540	540	560	\\img\1.bmp	20000	36	3	20	1	0
4	Cincinnati CFV-800i	800	540	560	\\img\2.bmp	8000	36	3	20	1	0
5	Cincinnati CFV-800Ki	800	540	560	\\img\2.bmp	10000	36	3	20	1	0
6	Cincinnati CFV-800Si	800	540	560	\\img\2.bmp	20000	36	3	20	1	0

Figure 6.10: Suitable Three Axes Machine Tool Selection

Three axis machine tool's work space is cuboids, around which the cutter can reach by moving independently or simultaneously along the axes. Maximum capacity along the three transverse axis is identified using the range calculated using the created software. Presence of machining feature along any other orientation other than positive Z axis would require changing the orientation of the machining feature along positive Z axis. Setting the

component along the orientation of the cutting tool would require halting of the machining process and then changing. This would result in increased down time of machine tool, which can be reduced by increasing the freedom of machine tool. Freedom of machine tool can be increased by integrating additional axis, if the spindle or work piece is allowed to pivot and rotate at angles. Machining having three traverse and single additional rotational axis are called 4-Axis machine tools.

6.4.2 Choice of 4-Axis Machine Tool

An analysis of the component by the created software provides the user with additional rotational axes that are required for the machining setup as shown in Figure 6.11. Choice for additional rotational axis depends on the user. User can include the required rotation axis and angle of rotation in the search for selection of machine tool from database as shown in Figure 6.12.

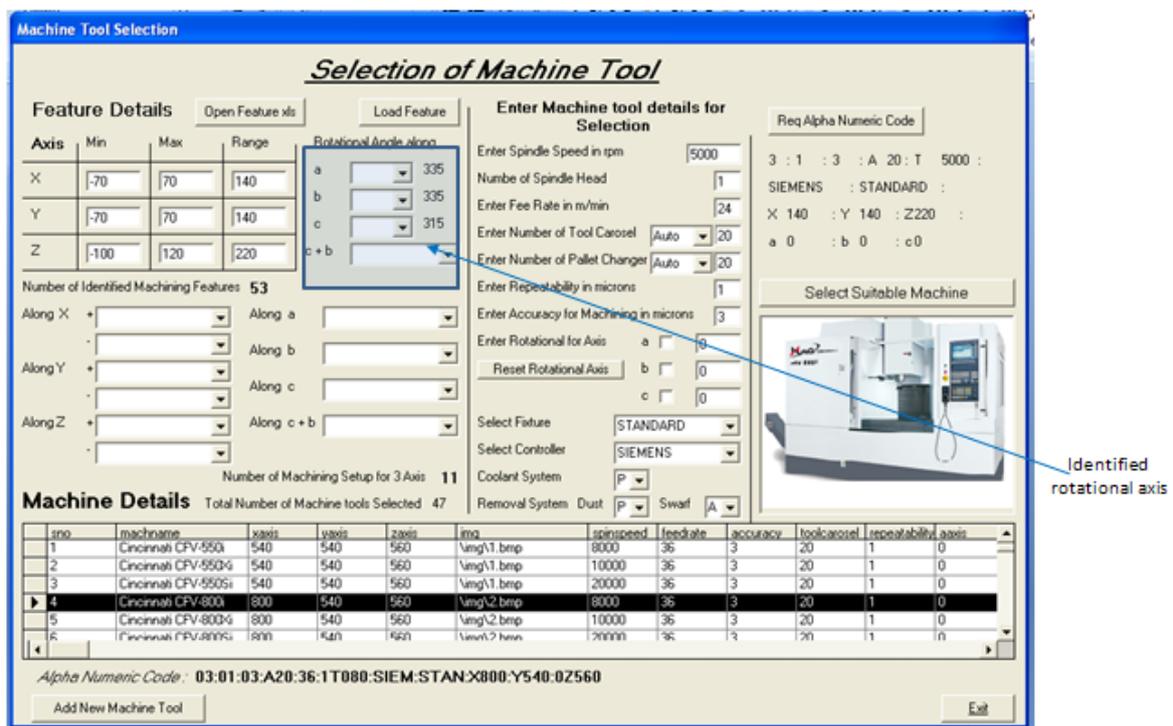


Figure 6.11: Identified rotational axis

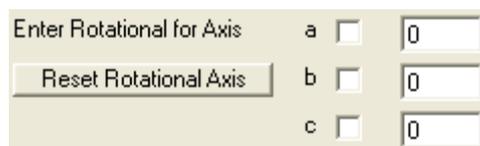


Figure 6.12: Selection option for additional rotational axis

The rotational axis can be provided by a, b or c, along X, Y or Z respectively which can orient the component in additional direction to reduce setups. Additional rotational axis a, b and c can provide setup for machining feature which orient between XZ, YZ, and XY axes respectively. Rotational axis c is not a preferred axis as the component does not provide any change in the orientation of the component. Conjunctions of c rotation with any other rotational axis creating the 5-axis machine are useful for orientation. Figure 6.13 illustrates the reduction of setup for machining the component with inclusion additional rotational axis along a, b, or c.

Inclusion of an axis		
Along Axis	Setups Angle	Number of Setup
+Z	Initial Datum Setup	1st
-Z	YES	2nd
a	25deg, 335deg	3 rd
b	25deg, 335deg	4 th and 5th
c	135deg, 315deg	6 th and 7th
c + b	135+45deg, 315+45deg, 315+48deg	8 th , 9 th and 10 th

Inclusion of b axis		
Along Axis	Setups Angle	Number of Setup
+Z	Initial Datum Setup	1st
-Z	YES	2nd
a	25deg, 335deg	3 rd and 4 th
b	25deg, 335deg	5th
c	135deg, 315deg	6 th and 7th
c + b	135+45deg, 315+45deg, 315+48deg	8 th , 9 th and 10 th

Inclusion of c axis		
Along Axis	Setups Angle	Number of Setup
+Z	Initial Datum Setup	1st
-Z	YES	2nd
a	25deg, 335deg	3 rd and 4 th
b	25deg, 335deg	5 th and 6th
c	135deg, 315deg	7th
c + b	135+45deg, 315+45deg, 315+48deg	8 th , 9 th and 10 th

Figure 6.13: Reduction of setup with inclusion of single rotary axis

6.4.3 Choice of 5-Axis Machine Tool

Inclusion of two rotational axis		
Along Axis	Setups Angle	Number of Setup
+Z	Initial Datum Setup	1st
-Z	YES	2nd
a	25deg, 335deg	3 rd
b	25deg, 335deg	4 th
c	135deg, 315deg	5 th
c + b	135+45deg, 315+45deg, 315+48deg	6 th

Figure 6.14: Reduction of setup with inclusion of single rotary axis

Additional axes combination ab, bc, or ca can be included to existing 3 axis setup for a 5-axis machine tool to reduce the number of setup. Figure 6.14 shows the possible 5 axis combinations and their setups.

6.5 Working of Soft wares

The Figure 6.15 shows the Pro/Engineering application for CAD modelling. Created software is invoked within the application using the sub-menu “Auxiliary application” which is under main menu option of “Tools” as shown in Figure 6.16. The selection of the menu will open up a new window called “Auxiliary Applications” window as shown in Figure 6.17.

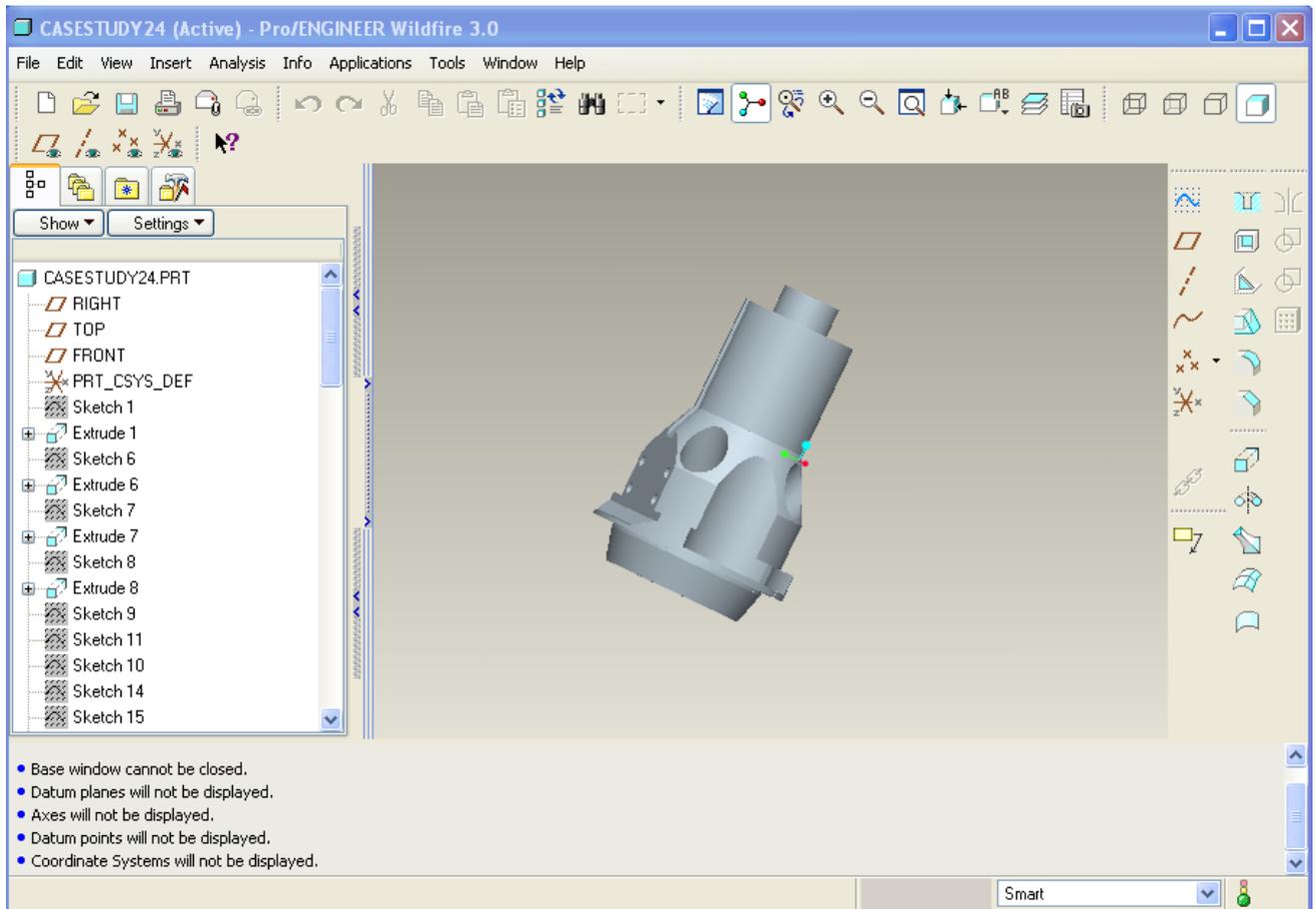


Figure 6.15: Pro/Engineer Application for CAD modelling

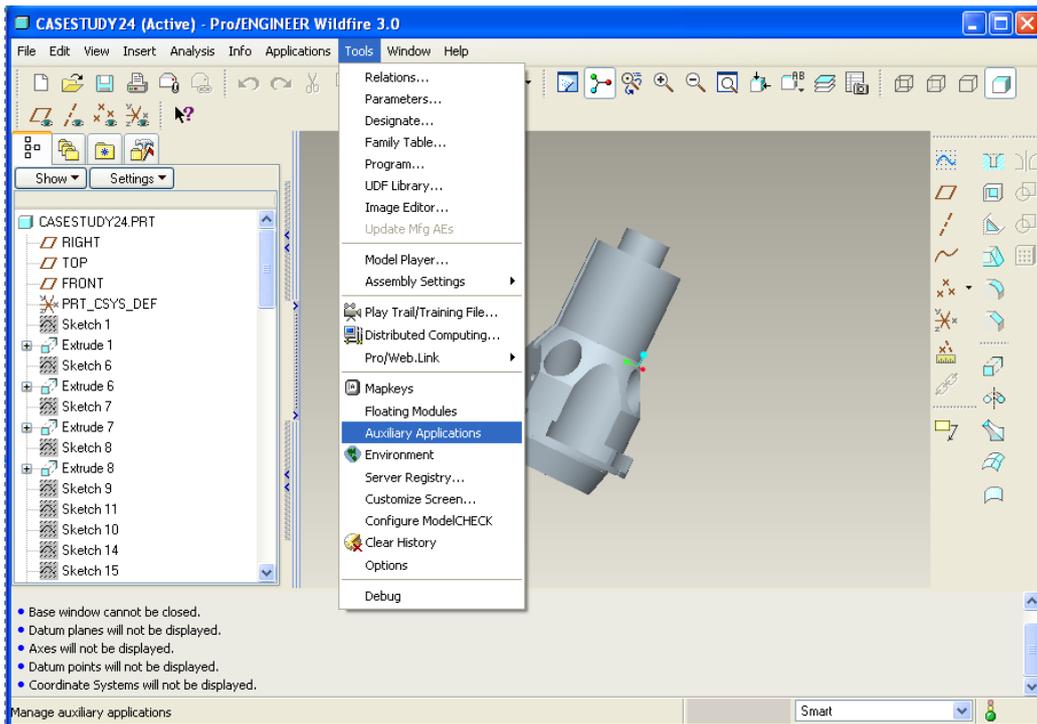


Figure 6.16: Invoking created software using Auxiliary Applications

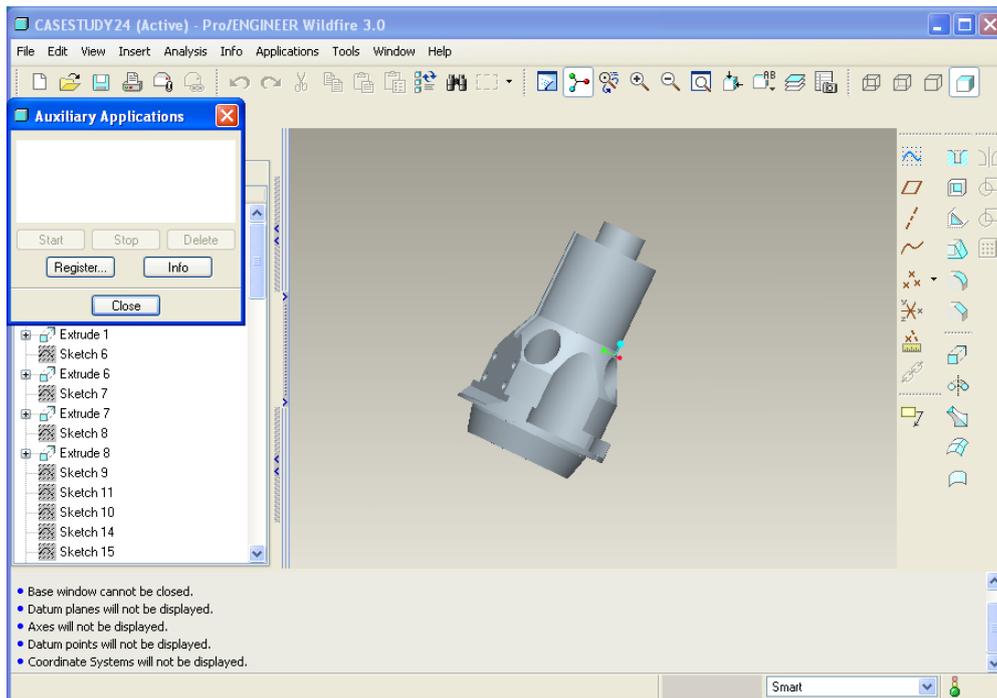


Figure 6.17: Auxiliary Application window

Using the auxiliary application's window the created registry file is opened using the register button as shown in Figure 6.18 which links the created software with Pro/Engineering

application. After locating the registry file, the file is started using the stop/start button on the window as shown in Figure 6.19 and Figure 6.20 shows the application running.

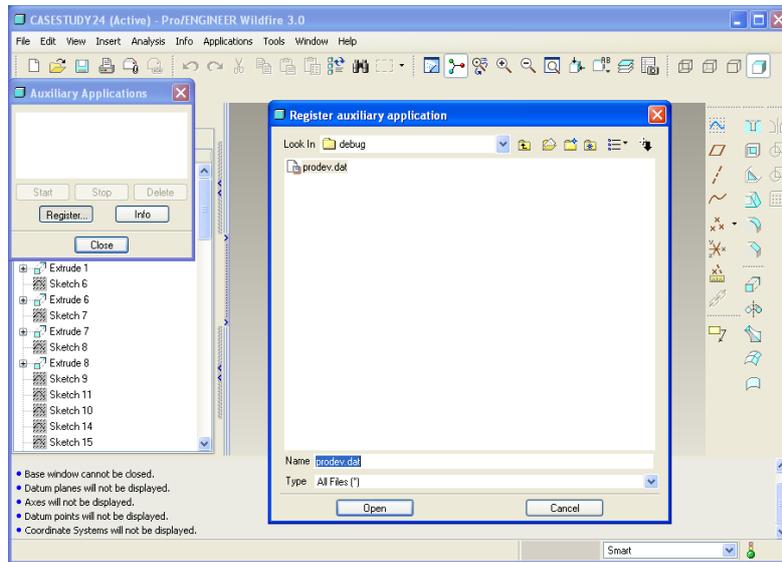


Figure 6.18: Opening the registry file using auxiliary applications

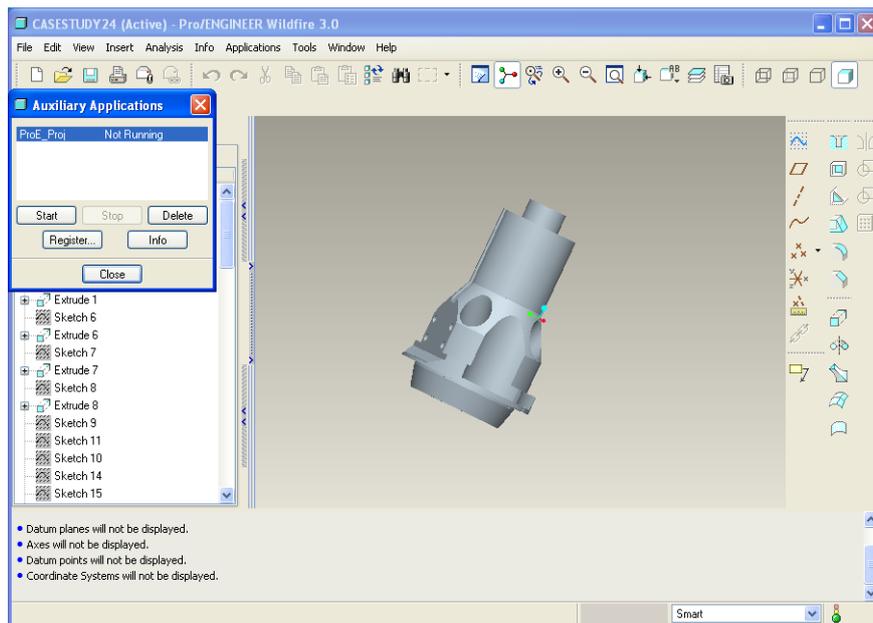


Figure 6.19: Start/Stop of registry file

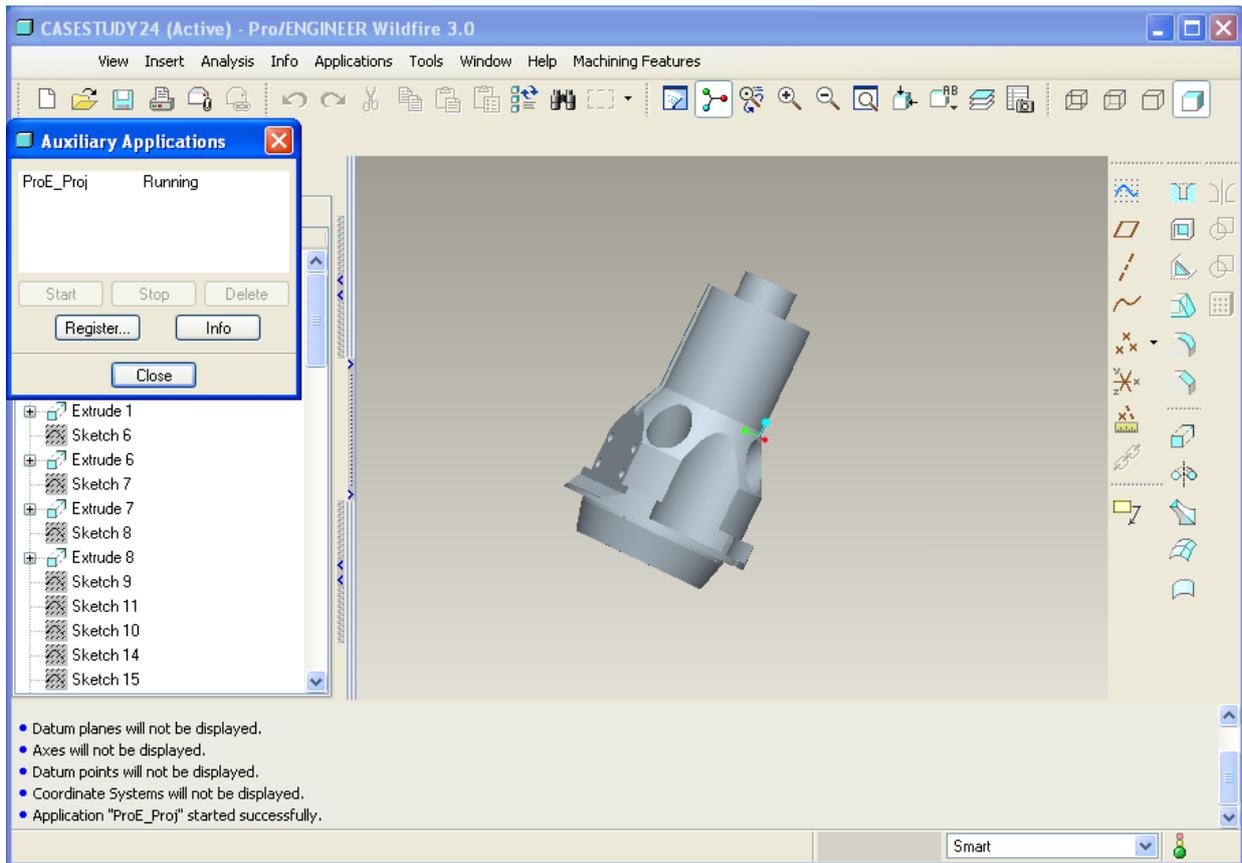


Figure 6.20: Running of the registry file in Auxiliary Application window

Once the registry file link's the created software with the Pro/Engineering application a new menu called "Machining Features" with its sub-menu are created next to "Help" menu as shown in Figure 6.21. The created menu has the sub menus of the entire machining feature that are created using in the API software and finally included a menu called "Select Machine". On selection of the sub menu to identify a specific machining feature, the API software would highlight the edges of surfaces which create the machining feature as shown in Figure 6.22. Highlighted surfaces are selected and accepted using the select window as shown in Figure 6.23. Further instance of the machining feature is highlighted and the procedure is repeated until all the requested machining features are highlighted. The surface selected are passed on to various Pro/TOOLKIT functions to identify the data required, which are stored into flat file database.

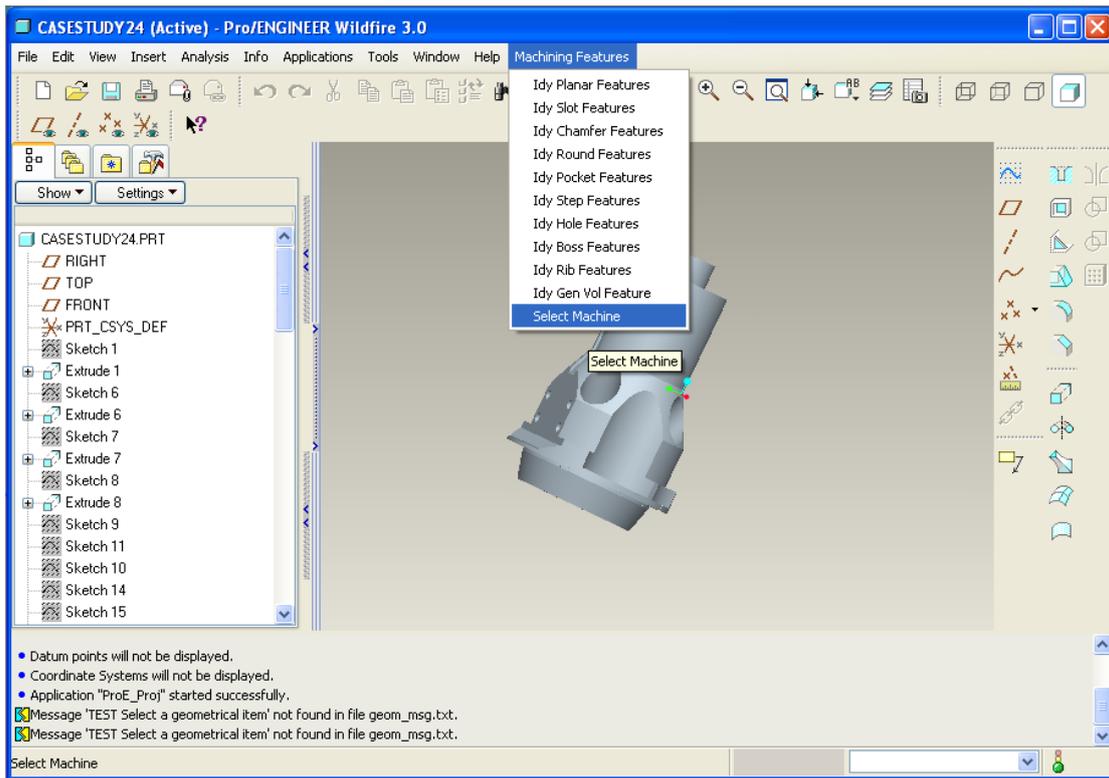


Figure 6.21: Machining Features menu and its sub menu

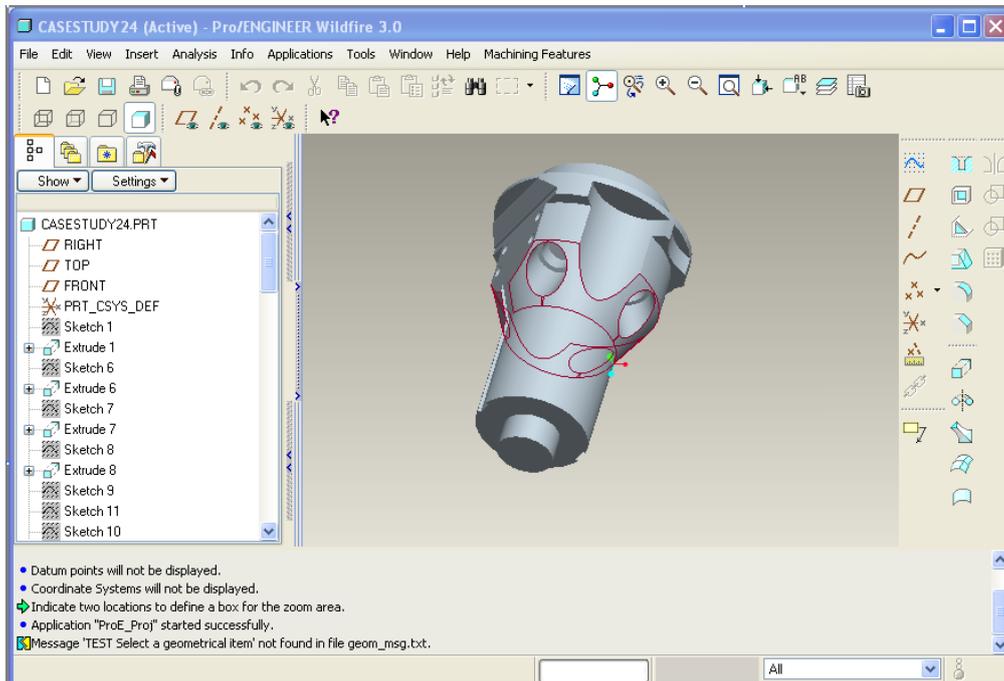


Figure 6.22: Machining feature highlighted

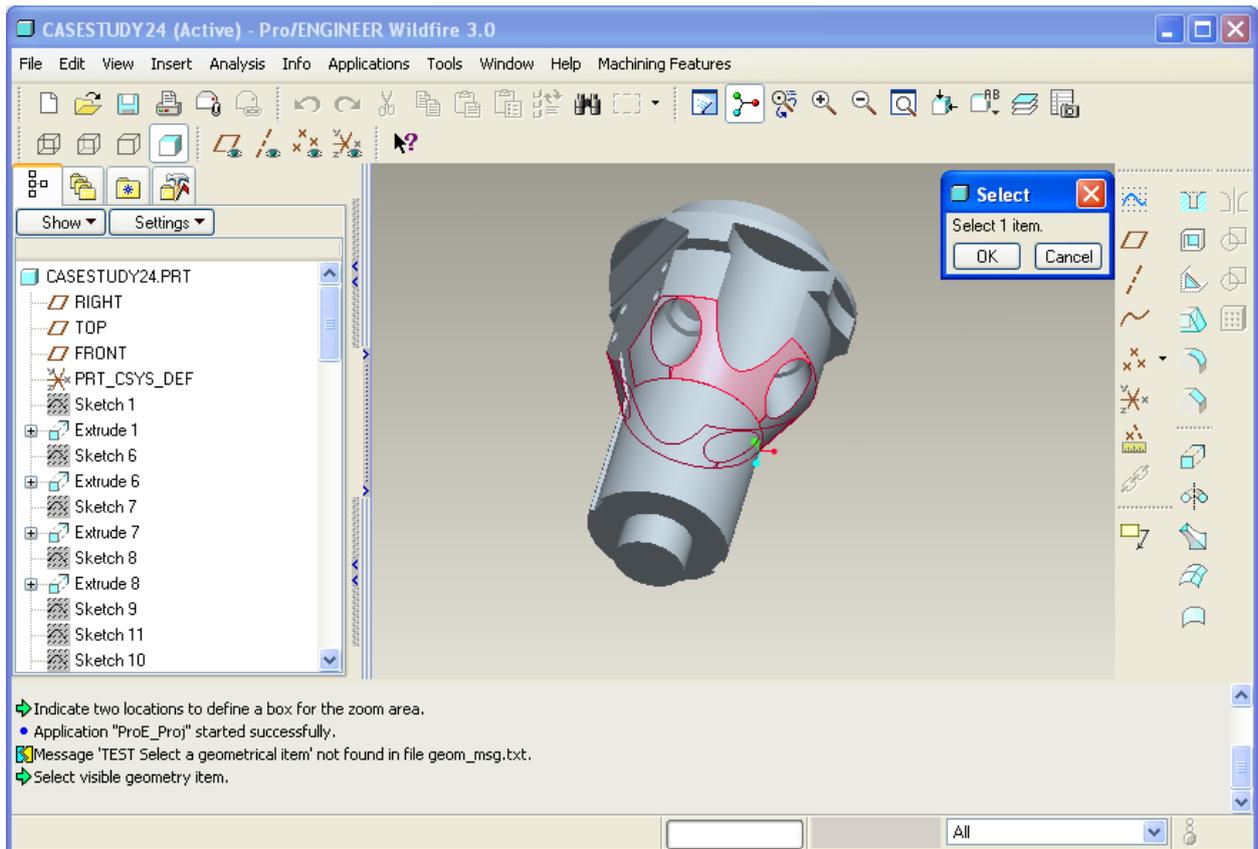


Figure 6.23: Select window to accept the selected surface

Using the Machining Feature’s menu, once all the machining features are identified, the “Select Machine” menu is used to open the visual basic software created as shown in Figure 6.24 to select a suitable machine tool using the data collected from API software. The created software consist a button called “Open Feature xls” to open the flat file database as shown in Figure 6.25 which can be saved into a structured file using spread sheet as shown in Figure 6.26.

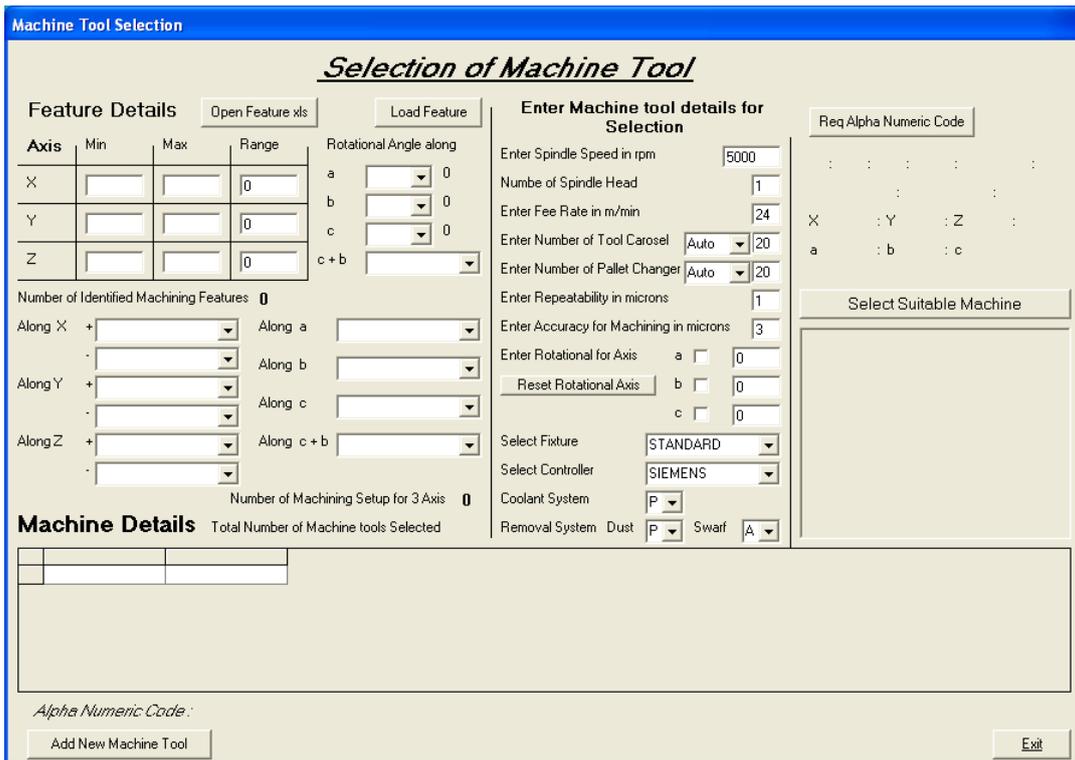


Figure 6.24: Visual Basic Software Created for Selecting Machine Tool

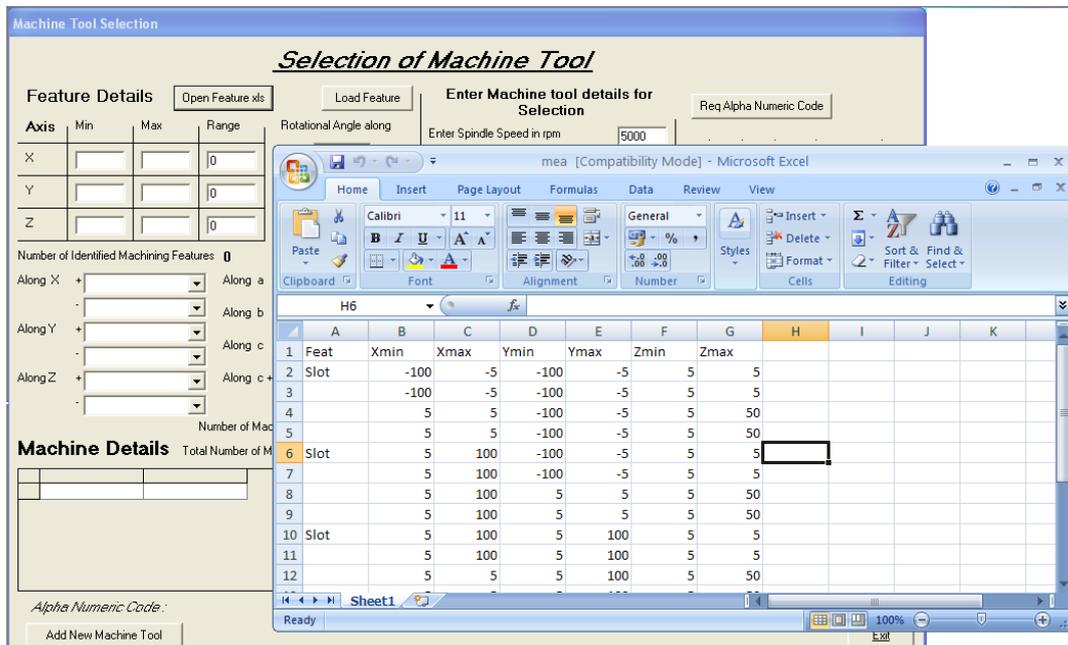


Figure 6.25: Flat file database saved as Structure database

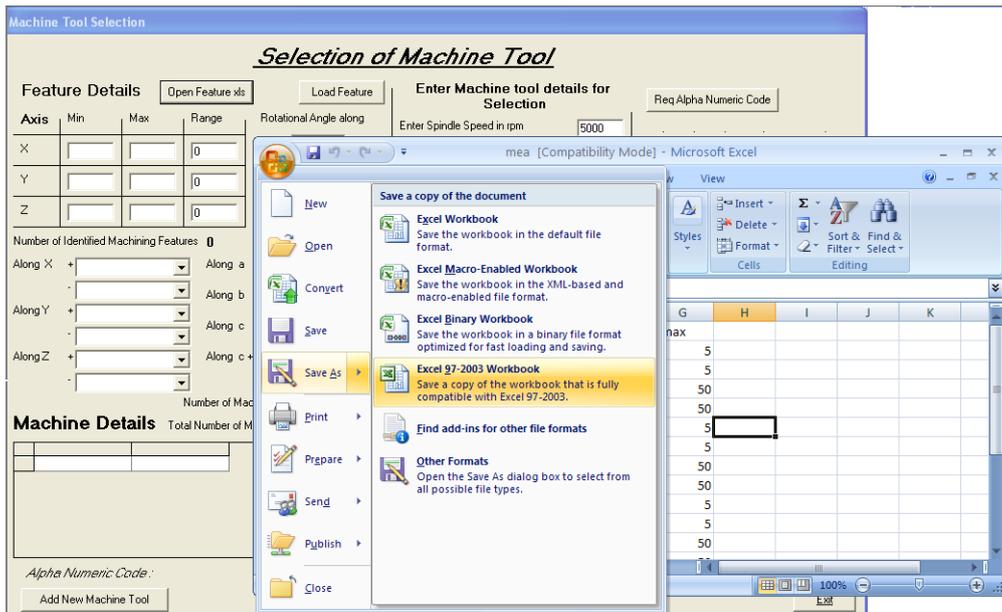


Figure 6.26: Saving Flat file to structure database

The next button called “Load Feature” which will analysis the database and identify a) range of machining, b) machining feature’s orientations, c) number of machining features, and c) number of setup required for machining. The identified details are shown in Figure 6.27.

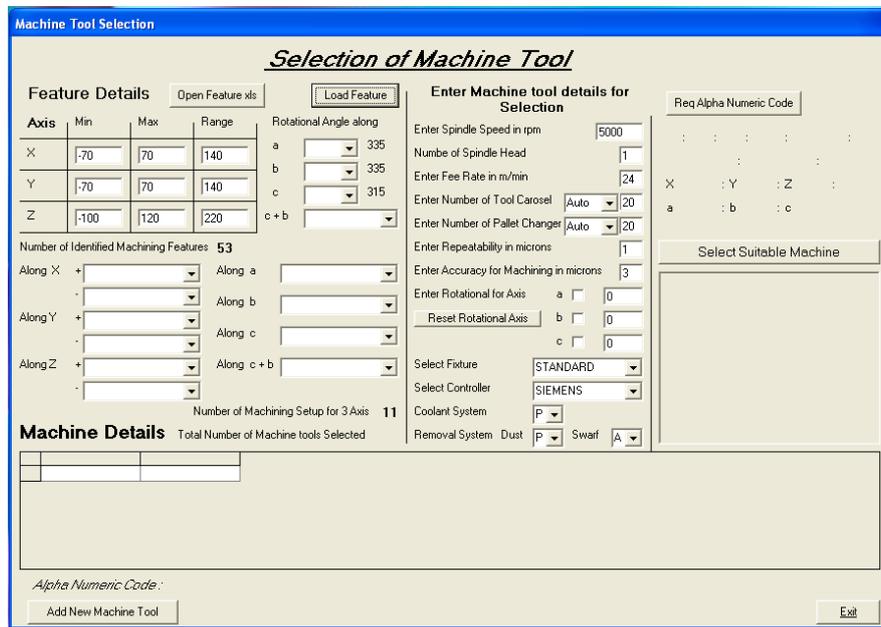


Figure 6.27: Identified details from structure data

The next section of the software separated using two vertical lines request the user to input further machining details. The button “Req Alpha Numeric Code” will now generated a alphanumeric code specific for the component with request machining details and is given as

output as shown in Figure 6.28. On Click of button “Select Suitable Machine” the optimal machines which match the requirements are selected using generated alphanumeric code. The Figure 6.29 shows the selected machine tool which are tabulated with their specifications.

Machine Tool Selection

Selection of Machine Tool

Feature Details Open Feature.xls Load Feature

Axis	Min	Max	Range
X	-70	70	140
Y	-70	70	140
Z	-100	120	220

Rotational Angle along

a 335

b 335

c 315

c + b

Number of Identified Machining Features: **53**

Along X + -

Along Y + -

Along Z + -

Along a

Along b

Along c

Along c + b

Number of Machining Setup for 3 Axis: **11**

Machine Details Total Number of Machine tools Selected

Machine	Code	Specs

Alpha Numeric Code :

Enter Machine tool details for Selection Req Alpha Numeric Code

Enter Spindle Speed in rpm:

Numbe of Spindle Head:

Enter Fee Rate in m/min:

Enter Number of Tool Carousel: 20

Enter Number of Pallet Changer: 20

Enter Repeatability in microns:

Enter Accuracy for Machining in microns:

Enter Rotational for Axis: a 0, b 0, c 0

Select Fixture:

Select Controller:

Coolant System:

Removal System: Dust Swarf

Figure 6.28: Generation of Alphanumeric code for the component

will request user to input details of machine tools as shown in Figure 6.30. The Window also provides further option to browse, modify and delete machine tools in the database

Chapter 7 – Summary and Conclusion

7.1 Summary

Machine Tools have been analysed with due considerations for axes, sizes, spindles, tool magazines, palettes and controllers. Their structural layout has been analysed based on the block structure method. Using the results of these analysis an alphanumeric code to uniquely represent a machine tool has been developed.

Machine tools available in the market have been analysed and alphanumeric codes for them have been developed and stored in a sample database. The database can be browsed and machine tools with chosen alphanumeric codes can be retrieved for detailed viewing.

A system has been established with Pro/Engineer software suite from which machining features and relevant information from a CAD model produced by Pro/Engineer can be extracted. A software written in 'C' has been developed using the API, Pro-toolkit for this extraction of information. A software system has been established to choose required machine tool using their characteristics machining features generated as alphanumeric code for the given machining job. Finally, a software incorporating the above and the required interfaces for inputting and outputting has been established. The software has been tested with several case studies and proven to be effective.

7.2 Contribution

Major Contributions of this research work are:

- Machine tools features such as axes, sizes, spindles, tool magazine, pallets, controller etc were identified to create alphanumeric strings which were in turn used for generation of alphanumeric code.
- Database of commercially available machine tools consisting of their machining features was created and generated alphanumeric code was also included.
- A bolt on software to Pro/Engineer was created using C program to identify the machining features and its parameters.

- Identified machining features and its parameters, along with required machining details of a component was used to generate alphanumeric code for any arbitrary component.
- Both the alphanumeric code was matched to select a suitable machine tool which was implemented using visual basic.

7.3 Limitation

- The selection of suitable machine tool is limited to vertical milling machine and its jobs.
- Database of machining tool is limited in this work, for commercial viability of the process, database has to be extensively populated.

7.4 Further Research

- Machining Features, which are identified, can be sequenced in order of priority for machining.
- With inclusion of cutting tool information, creating NC code using CAM can also be incorporated, as the parameters of the machining features are readily available.
- The selection process can further be extended to Turning centres and other types of milling machine with modification in the software.
- Use of feature information for cost estimation and to provide feed-back about consequences of design decisions can be implemented for selection of outsourcing job.

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