

**A FUZZY SET BASED SETUP PLANNING EXPERT  
SYSTEM CONSIDERING FIXTURING ASPECTS  
FOR MACHINING OF PRISMATIC PARTS**

A Thesis Submitted in Partial Fulfillment of the Requirements  
for the Degree of

**DOCTOR OF PHILOSOPHY**

by

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## CERTIFICATE

It is certified that the work contained in the Thesis entitled “**A Fuzzy Set Based Setup Planning Expert System Considering Fixturing Aspects for Machining of Prismatic Parts**” submitted by **Ms Manjuri Hazarika** to the Indian Institute of Technology Guwahati for the award of the degree of Doctor of Philosophy has been carried out under my supervision in the Department of Mechanical Engineering, Indian Institute of Technology Guwahati. This work has not been submitted elsewhere for the award of any other degree or diploma.

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***Dedicated to.....***

***My parents***

***My teachers***

***&***

***My family***

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## Synopsis

Systematic determination of the steps to convert a raw stock to a finished product is an important issue in manufacturing. It is the task of process planning to translate the design information of a part into manufacturing instructions. Process planning can be decomposed into several sequential phases, *viz.* design interpretation, process selection, setup planning, tolerance assignment, process parameter selection, and documentation [Xu *et al.* 2007]. Setup planning constitutes the core of a process planning system. Setup planning is the part of process planning concerned with the grouping of features into setups in their proper sequence, selecting datum for each setup, sequencing the setups and choosing appropriate machines, tools and fixtures. As manual planning is tedious and time consuming, efforts to automate process planning and setup planning have been going on since 1980s [ElMaraghy, 1993; Eversheim and Schneewind, 1993; Leung, 1996; Yip-Hoi, 2002; and Xu *et al.*, 2007]. A feasible and optimal setup plan involves a number of constraints that are mutually conflicting considering technological, geometrical and economical aspects of both design and manufacturing domain. Nevertheless, the ultimate goal of automating setup planning is to achieve the desired quality of the finished product at the lowest possible production cost and with the minimum manufacturing time.

For setup planning problems, conventional mathematical/logical algorithms are not readily available and applications of those do not yield satisfactory solutions. Moreover, setup planning has to be carried out in an environment of uncertainty. It incorporates expert knowledge in various stages collecting it from different sources. There may be uncertainty in the collected knowledge which affects the final outcome of the setup plan. Decision making in setup planning involves the use of uncertain knowledge to a large extent. Therefore, solution methods should be built on an intelligent architecture with the composite use of artificial intelligence (AI)

techniques. Expert system and fuzzy set theory are two important AI techniques. Expert systems are good at logic and fuzzy sets are best used for reasoning under uncertainty. Expert systems have been used for setup planning for their ability of reasoning, representation of large amount of knowledge, and explicit inference route [Joshi *et al.*, 1988; Sabourin and Villeneuve, 1996; Kim *et al.*, 1998; Liu and Wang, 2007]. The modular nature of expert systems makes them easier to encapsulate knowledge and expand them by incremental development. The benefit of using fuzzy sets is the ability to solve practical, real world problems, which invariably involve some degree of imprecision and uncertainty.

The major objective of the thesis is to explore the benefits of using expert system for setup planning and fuzzy sets to deal with the uncertainties associated with setup planning knowledge. Expert system is used for building the basic framework of the setup planning system. To simplify the task of expert system development, an expert system shell is used in this work. An expert system shell is a software system where the developer has to build the knowledge-base. The proposed setup planning expert system has been implemented on a PC using the expert system shell CLIPS, an acronym for C Language Integrated Production System [Giarratano and Riley, 1998]. CLIPS is designed to facilitate the development of software to model human knowledge and expertise. A program written in CLIPS consists of rules and facts. The fuzzy set based approach is used to manage uncertainty in the knowledge-base of the expert system, in particular, the uncertainty in feature precedence relations, and datum selection for each setup. Most of the previous research efforts considering uncertainty considered the uncertainty on the shop floor, *viz.* resource and capacity constraints, machine breakdown, and tool failure, but not the uncertainty in the knowledge-base. Consideration of fixturing constraints in setup planning is inevitable for generation of a feasible and robust setup plan. In view of it, fixturing requirements are incorporated into the setup planning expert system for machining of prismatic parts. Moreover, the developed setup planning expert system is capable of learning from feedback received from the shop floor and adapting to the actual condition during machining. An adaptive learning strategy is developed to receive feedback from actual production stage and modify the knowledge-base accordingly.

In the proposed setup planning system, a fuzzy set based approach is used to manage uncertainty with fuzzy membership grades. For a fuzzy input or output variable, membership grades are assigned to map numeric data to linguistic fuzzy terms. The problem of finding appropriate membership functions/membership grades for the fuzzy variables poses a challenge to the researchers. The knowledge of human experts plays a vital role in assigning these membership grades. Most of the time, different estimates of a fuzzy variable are decided based on expert's opinion. However, there is a need to optimize these estimates to enhance performance. Considering that the knowledge of an expert is available for the initial estimates of a fuzzy parameter, a methodology is proposed for fine tuning these estimates to enhance the performance of fuzzy set based system. It combines the best of an expert's knowledge and available experimental data to predict the membership grades of fuzzy parameters. The methodology is applied to the estimation of burr height in drilling holes in three different materials, *viz.* aluminium, mild steel, and cast iron. A series of experiments were conducted with these materials to study the effect of ductility, feed rate, and tool geometry on burr height in drilling. It is observed that fine tuning of the initial expert's estimates of membership grades of ductility, feed rate, and tool geometry enhances the performance of the burr height prediction system.

Surface roughness of the datum face is an important criterion to be considered for the selection of the datum during setup planning as it can affect the tolerances among the features. However, no theoretical model or experimental study is available in the literature that predicts the effect of datum surface roughness on the tolerances among the features of a part. In this work, an experimental study is conducted to investigate the effect of datum surface roughness on two geometric tolerances, *viz.* parallelism and perpendicularity in machining of prismatic parts. A series of experiments were carried out on a vertical milling machine and a universal milling machine using cast iron and perspex work materials. The experimental results were assessed with the hypothesis test using Student's *t*-test at 95% confidence level. This assessment is essential as some inherent statistical variation is always present in a machining process. In the present work, replicate experiments

were carried out to study the effect of datum surface roughness on parallelism and perpendicularity tolerances. The results of replicate experiments were used in two-sample  $t$ -test. Two-sample  $t$ -test is carried out to see whether for two samples of sizes  $m$  and  $n$ , the difference between sample means  $\bar{x}_1$  and  $\bar{x}_2$  is significant or not. A simplified model is proposed for interpreting the experimental results. Some more experiments were conducted in the universal testing machine to verify the validity of the proposed model and the results are in good agreement with the assumptions made for modelling. The knowledge gained from the experimental study is incorporated into the setup planning expert system in the form of IF-THEN rules. The knowledge is used to decide the datum surface roughness for achieving a particular tolerance level.

The output of the traditional setup planning approaches is limited and insufficient for the upstream process planning activity, such as fixture design. It is essential to estimate the range of process parameters, machining and clamping forces, fixture element sizes and layout during setup planning stage considering the feasibility of fixturing. In absence of this, the independent fixture design module may fail to generate feasible fixture plans leading to the need of redesigning of setups. These issues are not covered in detail in the existing setup planning approaches. There is a need to develop a robust and practical setup planning solution considering setup, fixturing and machining constraints simultaneously. In view of it, fixturing requirements are incorporated into the setup planning expert system for machining of prismatic parts. In addition to the normal setup planning information, the system can provide the following output: the range of depth of cut/feed and fuzzy machining and clamping forces for the features, approximate optimal locator and clamp layout, and sizes of the locators and clamps. The uncertainties associated with the work material, clamp material and clamping torque are considered by means of fuzzy arithmetic. Moreover, the existing setup planning systems deal with the conceptual fixture design phase by selecting the datum features. The proposed setup planning system performs configuration design and preliminary detailed design of fixtures in addition to selection of datum. The fixture designer can further

optimize the fixture plan by taking input from the setup planning module. This methodology helps in improving the overall efficiency of the process plan.

The important contributions of the present thesis are summarized below:

- By executing the setup planning expert system for different example parts, it is observed that setup plans are obtained investing very limited amount of time. Given the information about different features present in a part, machining operations, machine tools, cutting tools and material properties as input, the developed setup planning system performs the tasks of setup formation, operation sequencing, datum selection for each setup, and generation of information related to fixturing.
- Most of the previous work dealing with uncertainty considered the uncertainty in shop floor and resources, *e.g.* resource and capacity constraints, machine breakdown, and tool failure. The present setup planning system is capable of dealing with uncertainty in the knowledge-base. The fuzzy set based approach used to manage uncertainty in the knowledge-base, in particular feature precedence relations and datum selection, gives agreeable results.
- The methodology developed for fine tuning of the initial expert's estimates of fuzzy parameters has enhanced the performance of the burr height prediction method. This ensures the validity of the proposed methodology for fine tuning the initial membership grades of fuzzy parameters.
- In the literature, not much work is available that relates the effect of datum surface roughness to the geometrical tolerances of a component. In this work, an experimental study is conducted to study the effect of datum surface roughness on parallelism and perpendicularity tolerances. Based on the knowledge gained from the experimental study, the datum surface roughness can be ascertained for attaining a particular tolerance level.
- Most of the existing setup planning systems deals with the conceptual fixture design phase by selecting the datum features. The proposed setup

planning system performs configuration design and preliminary detailed design of fixtures in addition to selection of datum. The setup plan provides sufficient input to the fixture designer in terms of range of recommended depth of cut/feed, fuzzy machining and clamping forces, approximate optimal locator and clamp layout and sizes of the locators and clamps. The uncertainties associated with the work material, clamp material and clamping torque are considered by means of fuzzy arithmetic.

- It is observed from the example parts presented in the thesis that optimized locator and clamp layout gives a much lower value of the norm of the locator reactions than the value given by the initial locator and clamp layout. A strategy is developed to decide suitable dimensions of the locators and clamps.

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## Nomenclature

$A$	Cross sectional area of the locator
$a$	Index in Equation 6.19
$a$	Value of burr height at membership grade 0 in Equation 4.21
$b$	Value of burr height at membership grade 0.5 in Equation 4.21
$b$	Radial depth of cut
$CV$	Coefficient of variation
$c$	Value of burr height at membership grade 1 in Equation 4.21
$D$	Cutter diameter
$D_L$	Diameter of the locator button
$d$	Axial depth of cut
$d_{\text{clamp}}$	Diameter of the clamp
$d_e$	Additional depth of cut in Equation 5.5
$E$	Equivalent Young's modulus of elasticity of clamp and fixture element in Equation 6.13
$E_c$	Young's modulus of elasticity of the clamp material
$E_f$	Young's modulus of elasticity of the fixture element
$E_L$	Young's modulus of elasticity of the locator material
$E_w$	Young's modulus of elasticity of the workpiece material
$F$	Vertical component of cutting force in Equations 5.8 and 5.9
$F_a$	Axial component of cutting force
$F_c$	Cutting force
$F_{\text{clamp}}$	Clamping force
$F_r$	Radial component of cutting force
$F_t$	Tangential component of cutting force

Nomenclature

$F_{Th}$	Thrust in drilling
$F_x$	Cartesian component of cutting force in $x$ -direction
$F_y$	Cartesian component of cutting force in $y$ -direction
$F_z$	Cartesian component of cutting force in $z$ -direction
$f$	Feed per tooth in Equation 6.21
$f$	Fuzzy set theoretic operator in Equation 4.18
$H$	Height of the locator button
$h$	High estimate of a fuzzy parameter
$h$	Height of the workpiece in Equation 5.5
$J$	Polar moment of inertia of the clamp screw in Equation 6.15
$k$	Proportionality constant in Equation 6.33
$k$	Stiffness of the springs at datum surface in Equations 5.8 and 5.9
$k$	Number of independent observations in Equation 4.19
$k_p$	Proportionality constant in Equations 5.10 and 5.11
$L$	Height of the locator
$L$	Vertical height in Figure 6.3
$l$	Low estimate of a fuzzy parameter
$l_L$	Locator diameter
$m$	Most likely estimate of a fuzzy parameter
$n$	Sample size
$n_t$	The number of teeth/flute of the cutter
$P$	Normal force acting at the fixture-workpiece interface
$P_L$	Load on the locator on primary datum
$P_y$	Normal force to initiate yield in the workpiece material in Equation 6.11
$R$	Equivalent radius of curvature of clamp and fixture element in Equation 6.12
$R_a$	Center line average (CLA) surface roughness value
$R_{clamp}$	Radius of curvature of the spherical clamp
$R_f$	Radius of curvature of the fixture element
$R_i$	Locator reaction forces ( $i = 1$ to 6)

$R_L$	Radius of curvature of the locator button
$R_{\min}$	The minimum radius of curvature of the spherical clamp
$R_{\max}$	The maximum radius of curvature of the spherical clamp
$R_t$	Peak to valley roughness height of the workpiece surface
$R_w$	Radius of curvature of the workpiece contact surface
$r_{\text{clamp}}$	Radius of the clamp
$S$	Standard function in Equation 4.21
$s$	The height of the spherical clamp tip in Figure 6.6
$s$	Standard deviation
$T$	Clamping torque in Equation 6.14
$T_D$	Torque in drilling
$t$	Undeformed chip thickness in Equation 6.19
$t$	Parameter in Student's $t$ -test
$U_s$	Specific cutting energy
$\bar{x}$	Sample mean
$\bar{x}_H$	Mean of maximum parallelism tolerance for the highest datum Roughness cases
$\bar{x}_L$	Mean of maximum parallelism tolerance for the lowest datum Roughness cases
$Y$	The yield stress of the workpiece material in compression
$y$	Vertical distance in Figure 6.3
$z$	The number of axial elements comprising the axial depth of cut
$\alpha$	Weight factor in Equation 4.7
$\beta$	The helix angle of the cutter
$\delta$	Deflection of the locator on primary datum
$\delta_n$	Elastic deformation at workpiece-fixture contact surface
$\delta_1$	Deflection at point 1 in Figure 5.9
$\delta_2$	Deflection at point 2 in Figure 5.9
$\mu$	Membership grade of a fuzzy variable

Nomenclature

$\mu_c$	Computed membership grade for burr height in Equation 4.15
$\mu_{duc}$	Membership grade for ductility of the workpiece material
$\mu_{feedrate}$	Membership grade for feedrate
$\mu_i$	Membership grade for fuzzy variables ( $i = 1$ to $n$ )
$\mu_o$	Observed membership grade for burr height
$\mu_{o datum}$	Overall membership grade for datum surface
$\mu_{tool}$	Membership grade for tool geometry
$\nu$	The engagement angle of the cutter
$\nu_f$	The Poisson's ratio of the fixture element
$\nu_m$	The maximum engagement angle of the cutter
$\nu_w$	The Poisson's ratio of the workpiece material
$\tau$	Allowable shear stress of the clamp material
$\psi$	The angle of lag of a point on the cutting edge due to helical cutting edge

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## Abbreviations

ACO	Ant colony optimization
AGFPO	Automatic generation of process outlines of forming and machining processes
AI	Artificial intelligence
ANFIS	Adaptive-network-based fuzzy inference system
ANN	Artificial neural network
APPS	Automatic Process Planning System
ART	Automated Reasoning Tool
ATC	Automatic tool changer
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CAPP	Computer-aided process planning
CIM	Computer integrated manufacturing
CLA	Central line average
CLIPS	C Language Integrated Production System
CUTTECH	Cutting Technology
CV	Coefficient of variation
DMG	Datum and machining feature graph
DOPS	Drilling operation planning system
DPP	Distributed process planning
EXCAP	Expert Computer-Aided Process-Planning
EXSYS	Expert System Shell
FEA	Finite element analysis
FPG	Feature precedence graph
FTG	Feature tolerance graph
GA	Genetic algorithm
GEOPS	GEnereren van OPSpanningen: the generation of setups

## Abbreviations

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GT	Group technology
GTWORKS	Group Technology Works
HI-MAPP	Hierarchical and Intelligent Manufacturing Automated Process Planner
LISP	List Processing
MC	Machining center
NP	Nondeterministic Polynomial-time
OMEGA	Outil Multi-Expertise en Gamme Automatique (automatic process planning multi-expert system)
OPPS-PRI	Optimised Process Planning System for Prismatic parts
PDT	Product Data Translator
PIPP	Prototype-based Incremental Process Planning
PROLOG	Programming in Logic
PROPLAN	Process Planner
PSO	Particle swarm optimization
QTC	Quick Turnaround Cell
RMS	Reconfigurable manufacturing system
RPP	Reconfigurable process planning
SA	Simulated annealing
SIPP	Semi Intelligent Process Planning
SIPPS	Synthetic interactive process planning system
STEP	Standard for the Exchange of Product Model Data
TAD	Tool approach direction
TOM	Technostructure Of Machining
TS	Tabu Search
TSP	Travelling salesman problem
UTM	Universal testing machine
XML	eXtensible Modeling Language

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## Introduction

Systematic determination of the steps to convert a raw stock to a finished product is an important issue in manufacturing. While manufacturing a product, ensuring that the product meets design specifications and is of required quality is not enough. The product should be cost-effective, and it should be completed in time. It is the task of process planning to translate the design information of a part to manufacturing instructions. In view of the importance of process planning for manufacturing a part, the present thesis explores process planning, in particular automating setup planning for machining of prismatic parts. Setup planning constitutes the core of a process planning system. A fuzzy set based setup planning expert system is developed which has the capabilities of uncertainty management in the knowledge-base and adaptive learning from shop floor feedback. Moreover, the proposed setup planning system provides fixturing information to the fixture designer in addition to the normal setup information. Process planning and setup planning are briefly introduced in Section 1.1–1.3. Objectives and organization of the thesis are presented in Sections 1.4 and 1.5 respectively, of this chapter.

### 1.1 Process Planning

Process planning is the post-design and pre-manufacturing activity that bridges the functional gap between design and manufacturing. It is the act of preparing detailed work instructions to produce a part with the available resources at the lowest possible cost and of the best quality. Process planning maps the design

information of a part to a number of manufacturing steps through which raw material is converted into finished product. A part may contain different features. A feature is a specific geometric shape formed on the surface, edge or corner of a workpiece. A machining feature is generated by a machining process. Some examples of machining features are face, hole, slot, step, pocket, chamfer, *etc.* Different machining operations such as turning, milling, and drilling are used to machine these features. In this work, milling is the basic machining operation used for machining of prismatic parts.

There are two types of process planning in manufacturing; machining process planning and assembly process planning. Different aspects of machining process planning are discussed in this work. The machining process planning can be decomposed into several sequential phases as given below [Xu *et al.* 2007]. Each phase is dependent on its previous phase and the different tasks to be performed within each phase are interrelated.

- Design interpretation: analysis of materials and surface finish, design dimensioning and tolerance analysis
- Process selection and machine selection: selection of machining processes for producing the features of the part, selection of machine tools and cutting tools
- Setup planning: setup determination, setup and operation sequencing, and fixturing
- Tolerance assignment: conversion of design dimensions and tolerances into working dimensions and production tolerances
- Process parameter selection: calculation of speed, feed and depth of cut for each machining operation
- Cycle time estimation, job allocation, cost evaluation, and documentation: estimation and balancing of machining cycle time in each setup, allocation of jobs for shop floor production, manufacturing cost evaluation, and documentation of process plan for future use

Process planning requires the creativity and analytical skills essential for design in addition to in-depth manufacturing knowledge needed for actual production. Typically in industry, these tasks are performed by experienced process planners and machinists. However, manual planning is tedious, time consuming and prone to human errors. In view of it, there have been many attempts to automate process planning using computers. This is referred to as computer-aided process planning (CAPP). With increase in demand for novelty and variety in products, standard computer aided design (CAD) and computer aided manufacturing (CAM) tools are used by the industries. Computer aided process planning integrates both CAD and CAM to create a proper environment for computer integrated manufacturing (CIM). The benefits that can be derived from CAPP are manifold as follows:

- CAPP bridges the functional gap between CAD and CAM.
- It enables concurrent engineering and builds a proper environment for CIM.
- CAPP generates detailed, complete and consistent process plans.
- Overall manufacturing cost is reduced by reducing planning time, direct labour, *etc.*
- CAPP replaces manual planning which is tedious and prone to human errors.
- It reduces manufacturing lead time and enhances productivity.

The CAPP approaches can be broadly divided into two categories [Scallan, 2003]: variant CAPP and generative CAPP. The variant approach was the first approach used by the CAPP developers. The variant CAPP is implemented based on group technology (GT) and parts classification and coding system. The parts are classified into part families according to their geometric similarities and manufacturing characteristics. Standard process plans for each part family are stored in a part family matrix. To obtain a process plan for a new component, the code for the part is determined and the standard plan is retrieved if a similar part is found in the part family matrix. The process planner examines and edits the plan according to the requirements. The new plan can be put into the part family matrix for future reference. Variant approach has obvious disadvantages. Its limitations are that it is restricted to similar parts previously planned and experienced process planners are

required to modify the standard plan. Moreover, the cost involved in creating and maintaining databases for the part families is high. Due to these problems, variant approach is normally used when a well-defined part family structure exists and the new part closely conforms to the characteristics of the existing part families. Some variant process planning examples are CAPP (Computer-Aided Process Planning) [Tulkoff, 1978], TOM (Technostructure Of Machining) [Matsushima *et al.*, 1982], and GTWORKS (Group Technology Works) [Joshi *et al.* 1994].

The generative CAPP approach represents an alternative approach to automated process planning. The generative CAPP approach automatically creates process plans for a new part from scratch without referring to existing plans. Manufacturing knowledge is encoded into efficient software and automatic generation of process plan for a new part is possible using manufacturing knowledge and manufacturing information database. By applying decision making mechanism, a process planner's decision making logic is imitated. The decision making mechanism can be procedural algorithms, decision trees, decision tables and production rules. The main components of a generative CAPP system are

- a part description database,
- manufacturing resource database,
- manufacturing knowledge-base,
- decision making mechanism.

A major advantage of generative CAPP systems over variant systems is that they can provide process plan for a part for which no variant of the part exists which can be retrieved and modified. Another advantage of the generative approach is the generation of more consistent plans. Some examples of generative process planning systems are EXCAP (Expert Computer-Aided Process-Planning) [Davis and Darbyshire, 1984], PROPLAN (Process Planner) [Philips *et al.*, 1984], CUTTECH (Cutting Technology) [Barkocy and Zdeblick, 1984], SIPP (Semi Intelligent Process Planning) [Nau and Chang, 1985], HI-MAPP (Hierarchical and Intelligent Manufacturing Automated Process Planner) [Berenji and Khoshnevis, 1986], and QTC (Quick Turnaround Cell) [Kanumury and Chang, 1991]. The present research

work is concerned with generative CAPP approach. In particular, it deals with computer-aided setup planning for machining of prismatic parts.

## 1.2 Setup Planning in Machining Process

Setup planning is an intermediate phase of process planning. It is the act of preparing instructions for setting up parts for machining. A setup is basically the way in which the part is oriented and fixtured in one particular position in the machine tool for machining. As soon as the part's position is changed, it is considered a new setup. A group of features are machined in a setup without repositioning the part. Setup planning consists of the following steps:

- Setup formation, *i.e.* clustering of features and their machining operations into groups and assigning each group of features into different setups based on their tool approach direction (TAD) and tolerance relations. TAD is the direction from which a tool can access the feature to be machined. Features with a common TAD are generally grouped into the same setup. Tolerance relation with other features is an important criterion for setup formation. Normally, features with tight tolerance relations are assigned to the same setup.
- Datum selection, *i.e.* identifying the potential features which can serve as primary, secondary and tertiary datum for each setup. Primary datum is a face on the workpiece, resting on which the features in a setup undergo machining. Features sharing common TAD and datum are naturally grouped into one setup. Datum feature selection depends on several factors like surface area, orientation, surface finish, stability it provides, tolerance relation with other features, and intricacy and symmetry of the feature.
- Sequencing the setups and the machining operations within each setup. It is the most challenging task in setup planning. Setups and machining operations sequencing has the greatest impact on machined part accuracies. The decision making in sequencing setups and machining operations depends on certain constraints, *viz.* precedence constraints, different machining constraints and good manufacturing practice. These constraints are discussed in detail in Section 1.3.

Setup planning is traditionally performed by experienced process planners. However, manually developed setup plans heavily depend on the capability and experience of the process planner. Setup plans thus developed are prone to errors and difficult to standardise. Moreover, the knowledge and experience of the process planner is lost with his retirement. In view of it, researchers have been trying to automate setup planning. Although the efforts to automate setup planning have been going on since 1980s, it is still a complex task. This is because an optimum setup plan is dependent on a number of factors such as type and shape of raw material, availability of machines and tools, quantity of production, cost, desired tolerances and policy of management. Setup plan for mass production with high production volume is different from setup plan for job shop production with low production volume. An experienced process planner evaluates these factors mentally and takes an appropriate decision based on intuition and experience. It is very difficult to capture and store the knowledge of an experienced process planner in the form of a computer code. Nevertheless, the ultimate goal of automating setup planning is to achieve the desired quality of the finished product at the lowest possible production cost and with the minimum manufacturing time. This ultimate goal affects all decision making in setup planning. Realisation of this ultimate goal may vary with different manufacturing settings.

Figure 1.1 describes the framework for an ideal integrated automated setup planning system. It takes information on features, machining operations, machine tools and cutting tools as inputs. Based on these inputs, TAD of each feature, tolerance relations among the features, and precedence constraints and fixturing constraints are identified. Finally, applying manufacturing knowledge, feature grouping, setup formation, datum selection, and setup and machining operation sequencing tasks are performed and complete setup plans are formulated.

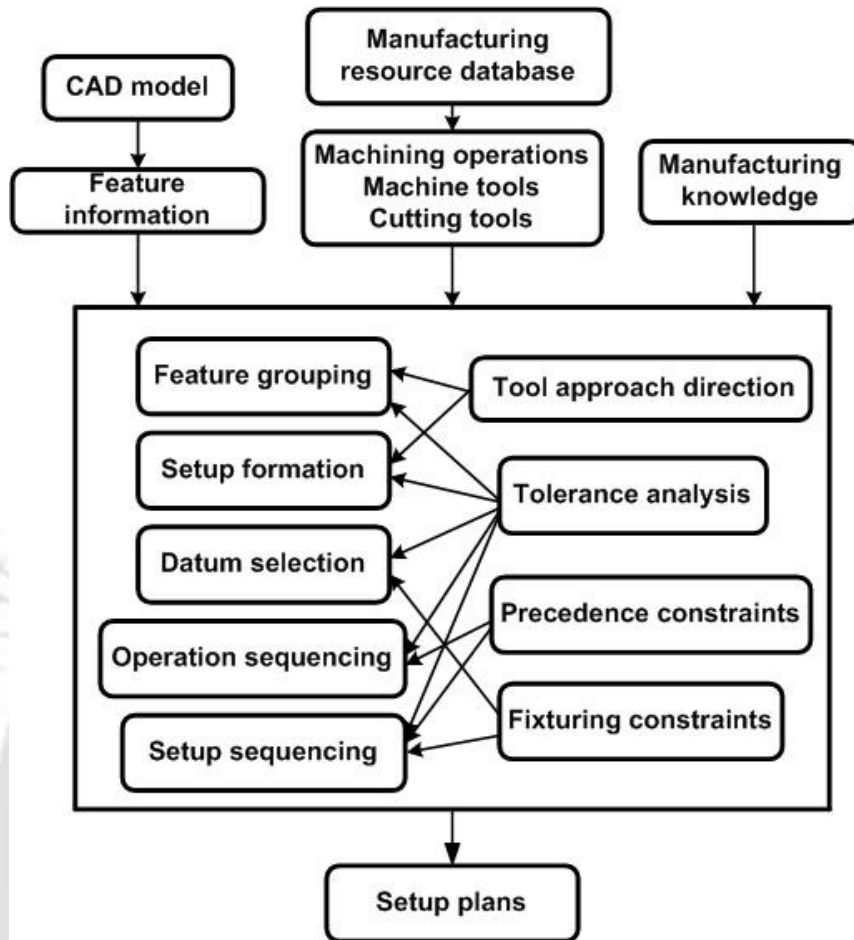


Figure 1.1. A setup planning system

### 1.3 Constraints to be considered in Setup Planning

A feasible and optimal setup plan involves a number of constraints and objectives that are mutually conflicting considering technological, geometrical and economical aspects of both design and manufacturing domain. Some constraints are very basic and of higher priority, which being violated, will result in infeasible setup plans. Interactions among the features lead to precedence constraints which are also called hard constraints. For example, machining of datum and reference features first is a hard constraint. There are also soft constraints, which being violated, will result in inferior setup plans. For example, attaining a particular tolerance is a soft constraint. Different constraints applicable to various stages of setup planning are discussed in the following subsections.

### 1.3.1 Tolerance Requirements

Attaining the specified design tolerances is a key factor for the quality as well as the functionality of a machined part. The ultimate goal of setup planning is to achieve desired part quality at the lowest possible cost and time. To attain critical tolerance relationship between two features of a part, priority wise, the following setup methods are to be used [Huang and Liu, 2003]:

Setup method 1: In this method, two features are machined in the same setup with the same datum so that setup errors are eliminated. Tightest tolerance features are to be preferably machined in the same setup. In setup method 1, the tolerance relationship is only influenced by the machine tool motion error.

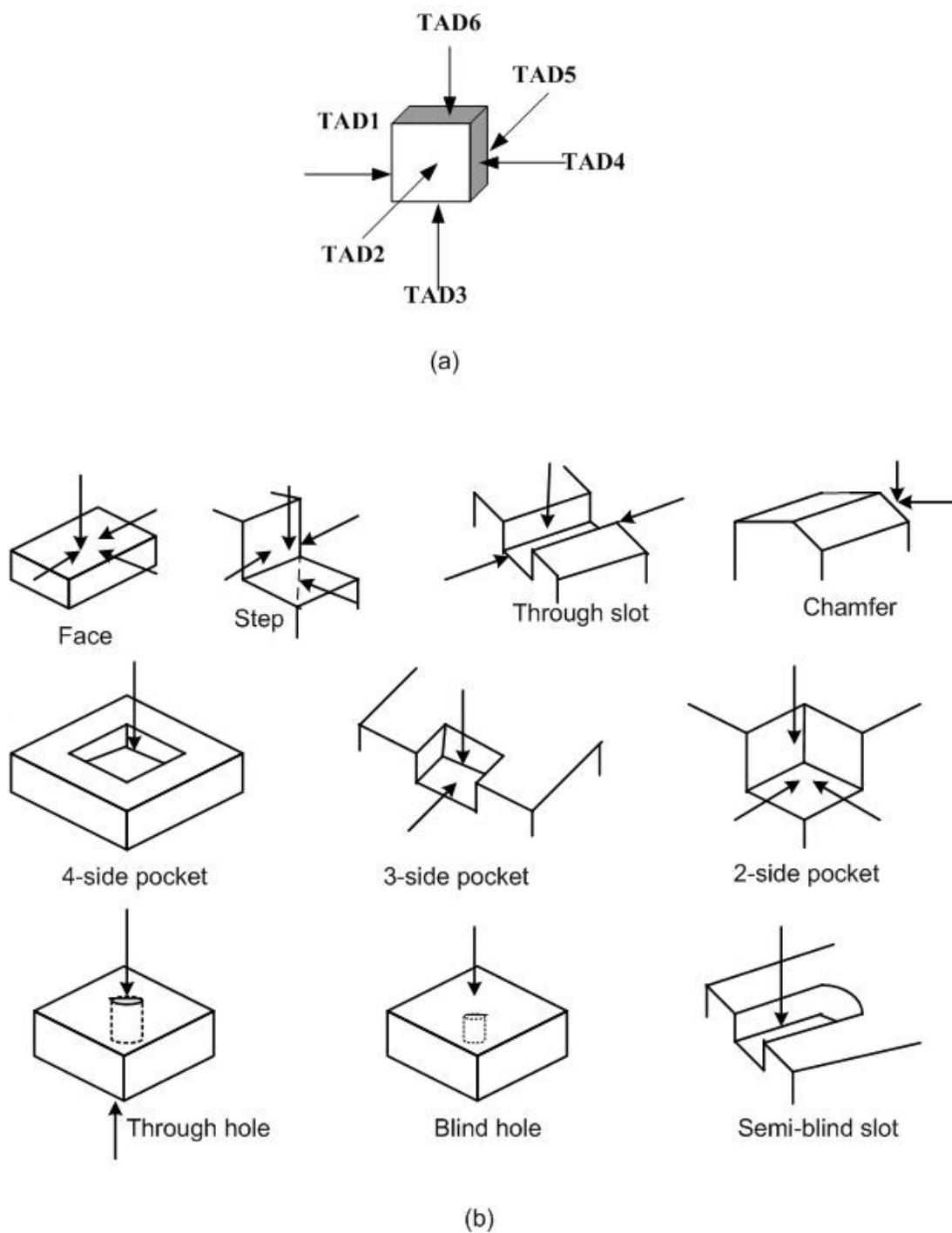
Setup method 2: In this method, one feature is used as datum for machining the other feature. This method is less accurate than setup method 1 as the tolerance relationship is influenced by both the machine tool motion error and setup error.

Setup method 3: Here, an intermediate datum is used to machine the two features in two different setups.

Setup method 3 is the least preferred method as a tolerance chain is formed for the dimensions obtained using this method. Tolerance will stack up and the resulting dimensions are less accurate compared to setup methods 1 and setup method 2.

### 1.3.2 Tool Approach Direction (TAD) of a Feature

Tool approach direction (TAD) of a feature is the unobstructed free path in which the tool can move and access the feature in a part to machine it. For each feature to be machined, the TAD is to be identified first. A prismatic part can have six TADs in +X, -X, +Y, -Y, +Z, and -Z directions, as shown in Figure 1.2 (a). A feature may have a single TAD or multiple TADs. Figure 1.2 (b) shows different features with their possible TADs. The features having a single common TAD are grouped together to form a common TAD feature group and assigned to the same setup for machining. The features having multiple TAD are assigned a single TAD based on its tolerance relation with other features. TAD of a feature is one of the most important factors in setup planning. For formation of setups, TAD and tolerance relation of a feature are considered.



**Figure 1.2.** Tool approach direction (TAD): (a) six available TAD for a prismatic part (b) different features with their TAD

### **1.3.3 Feature Interaction and Precedence Constraints**

Among the features comprising a part, certain feature interactions take place. Feature interaction leads to precedence relations in the machining sequence of the features. There may be area feature interaction where two features share a common face. In volumetric feature interaction, there is common volume to be removed. Parent-child type of feature interaction occurs where the child feature is embedded in the parent feature. Different strategies are applied to machine interacting features satisfying the precedence relations. Feature interaction is discussed in detail in Section 3.4.2.1, Chapter 3.

### **1.3.4 Fixturing Constraints**

Each setup has to fulfil some fixturing constraints to be fixturable and feasible at the same time. Locating accuracy, complete restraint of the workpiece, minimum deformation at the fixture-workpiece interface, fixturing stability, non-interference of the tool and fixture are some of the fixturing related constraint.

### **1.3.5 Datum and Reference Constraints**

The datum and reference requirements lead to the constraints that datum/reference features are to be machined prior to the related feature. As other features are located and dimensioned with respect to datum/reference features, datum/reference features are to be machined first.

### **1.3.6 Constraints of Good Manufacturing Practice**

There are some rules of thumb evolving from decades of experience which are practised in the industry. These are considered as good manufacturing practice. For example, in case of drilling of two concentric holes, a hole of smaller diameter is drilled prior to a hole of larger diameter. Similarly, the hole of longer depth is drilled prior to the hole of shorter depth if they are concentric. Drilling a hole first and then reaming for enlargement is preferred. Another example of good manufacturing practice is using the highest area face for primary datum for stability.

## 1.4 Broad Objectives of the Thesis

For setup planning problems, conventional mathematical/logical algorithms are not readily available and applications of those do not yield satisfactory solutions. Setup planning incorporates expert knowledge in various stages collecting it from different sources. However, there may be uncertainty in the collected knowledge which affects the final outcome of the setup plan. The use of artificial intelligence (AI) techniques in setup planning is gradually increasing, giving better results compared to traditional methods of setup planning. Expert system and fuzzy set theory are two important AI techniques. Expert systems are good at logic and fuzzy sets are best used for reasoning under uncertainty. Expert systems have been used for setup planning in CAPP for their ability of reasoning, and collection and representation of large amount of knowledge. Fuzzy set theory is used to handle uncertainty in the setup planning knowledge and reason with imprecise information. In view of it, the broad objectives of the present thesis are

- exploring the benefits of using expert system for setup planning and fuzzy sets to deal with the uncertainties associated with setup planning knowledge for machining of prismatic parts,
- developing a methodology for updating the knowledge-base of the setup planning system,
- incorporation of fixturing requirements in setup planning.

## 1.5 Organization of the Thesis

The thesis consists of eight chapters, which are organized as follows:

- The first chapter provides the introduction to process planning and setup planning along with the broad objectives of the research work and organization of the thesis.
- Chapter 2 presents a review of literature of the setup planning approaches. Traditional approaches as well as soft computing based approaches of setup planning are discussed. Finally, different challenging issues, scope and detailed objectives of the present thesis have been described.

- In Chapter 3, brief background knowledge of expert systems and CLIPS expert system shell is presented followed by the description of the different modules of the setup planning expert system. Development phases of the different modules are discussed in detail.
- Chapter 4 presents an introduction to fuzzy set theory followed by the fuzzy set based methodology for updating the knowledge-base of the expert system based on shop floor feedback. A strategy to deal with the uncertainties associated with feature precedence relations and datum selection using fuzzy sets is presented. Finally, a methodology is discussed for fine tuning the membership grades of fuzzy variables assigned by experts. The best of an expert's opinion and experimental data is combined for the fine tuning strategy.
- Chapter 5 presents an experimental study on the effect of datum surface roughness on parallelism and perpendicularity tolerances in milling of prismatic parts. A simplified mathematical model is developed to analyse the experimental findings. Statistical analysis of the experimental results is presented. The knowledge gathered from the experimental study is incorporated in the form of IF-THEN rules in the setup planning expert system for deciding the datum surface roughness for attaining a specified tolerance.
- Chapter 6 presents the fixturing constraints considered in the setup planning expert system. Methodology for generating fixturing related information is described in detail with an example. Uncertainties associated with the workpiece material, locating and clamping material, and clamping torque are dealt with fuzzy arithmetic.
- Illustrative examples are presented in Chapter 7.
- Chapter 8 presents the conclusions and scope for future work followed by references and appendices.

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## Review of Literature

### 2.1 Introduction

Automating setup planning is regarded as one of the most important activities in computer-aided process planning (CAPP). Setup planning is the part of computer-aided process planning concerned with the grouping of features into setups in their proper sequence, selecting datum for each setup, sequencing the setups and choosing appropriate machines, tools and fixtures. Although the efforts to automate setup planning have been going on since 1980s, it is still a complex task. A feasible and optimal setup plan involves a number of constraints that are mutually conflicting considering technological, geometrical and economical aspects of both design and manufacturing domain.

Automatic setup planning has been an active research area in the last two decades and it is widely investigated by various researchers. Automatic setup planning approaches found in the literature are widely diversified in terms of objectives, constraints and techniques used. Many researchers have addressed this problem from different perspectives and proposed different methods of setup planning based on analysis of part geometry, tool approach direction, tolerance requirements, precedence constraint analysis, fixtures needed, and manufacturing resources. Some important review articles on setup planning and process planning are found in ElMaraghy [1993], Eversheim and Schneewind [1993], Leung [1996], Yip-Hoi [2002], and Xu *et al.* [2007]. ElMaraghy [1993] and Eversheim and Schneewind [1993] provide good perspectives on the future developments of CAPP. A comprehensive review of industrial perspectives of CAPP, models of CAPP, and integration of CAPP with product design and production planning is presented along with the future trends in CAPP. Leung [1996] classified the literature on CAPP into

twelve logical areas of interest and analyzed the advantages and disadvantages of various process planning methods. Yip-Hoi [2002] presented an overview of the research work in CAPP in the past two decades along with the recent developments in feature recognition techniques. In a recent work, Xu *et al.* [2007] presented a review and analysis of various automatic setup planning approaches. The ultimate goal, constraints and various sub-tasks of setup planning are identified and a definition of setup plan optimality is presented.

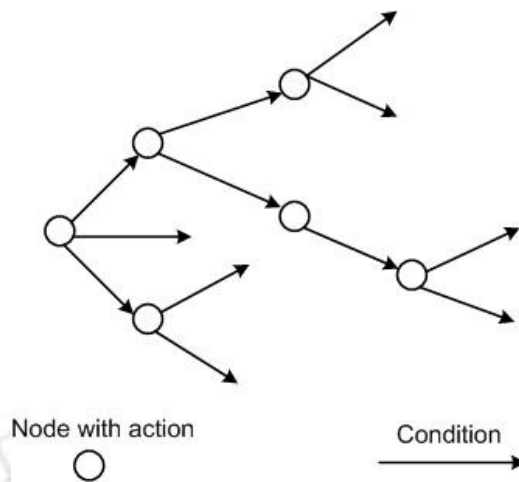
In this chapter, a review of available literature in the area of setup planning is presented in different sections. Section 2.2 discusses the traditional approaches of setup planning. Section 2.3 presents the various soft computing based approaches of setup planning. In Section 2.4, summary of literature review is presented and challenging issues in setup planning are discussed. Finally, detailed objective of the present work is presented in Section 2.5.

## **2.2 Traditional Approaches of Setup Planning**

Traditional approaches such as decision trees, decision tables, group technology (GT), and algorithms and graph theory have been used for solving the problem of setup planning. In the following subsections, a brief review of the application of these approaches in setup planning is presented. Pros and cons of different approaches are also discussed.

### **2.2.1 Decision Tree, decision Table and GT based Approaches**

Decision trees and decision tables are useful decision making tools. A decision tree is a way to represent information and knowledge. Conditions (IF) are set as branches of the tree and predetermined actions (THEN) can be found at the junction/node of each branch. The condition specified on each branch must be satisfied in order to traverse that branch. If the condition specified on a branch is true, then that branch can be traversed to reach the next node and this process is continued until a terminal point on the tree is reached. If the condition specified on a branch is false, then another branch may be taken. Figure 2.1 shows the structure of a decision tree.



**Figure 2.1.** Structure of a decision tree

The algorithm for implementing a decision tree may be written in any of the procedural programming languages such as FORTRAN, PASCAL, C, *etc.* GT codes and special descriptive languages are used for representing the part description. GT uses similarities between parts to classify them into part families. In the context of machining process planning, a part family consists of a set of parts that have similar machining requirements. An appropriate classification and coding system is to be used for the entire range of parts produced in a shop. All the existing parts are coded following the adopted scheme for coding. Each part family is then represented by a family matrix. The next step is to prepare a standard process plan that can be used by the entire part family. The standard process plans are then stored in a database and indexed by family matrices. Example of some commercially available GT coding systems are Opitz coding, KK-3 coding, MICLASS coding, DCLASS coding, *etc* [Chang *et al.*, 1998].

An example of the application of decision tree in generative CAPP is EXCAP (Expert Computer-Aided Process-Planning) [Davis and Darbyshire, 1984]. EXCAP generates process plans for machining symmetric rotational components. It uses a decision tree to represent possible operation sequences and backward chaining logic for decision making. Knowledge is represented by production rules. M-GEPPS is another CAPP system which uses decision tree for process planning of rotational parts [Wysk *et al.* 1988]. KK-3 GT coding is used for providing part information as input to the system. Eight different types of lathe machine operations, *viz.* cut-off,

facing, turning, drilling, boring, reaming, thread cutting and tapping can be planned by M-GEPPS.

Chitta *et al.* [1990] developed a decision support system for process planning of both rotational and prismatic parts. The system is capable of producing process plans for parts using different machining operations such as turning, drilling, reaming, boring, slotting, milling, thread cutting, *etc.* Opitz GT codes are used for providing input information of the parts, machine tools and cutting tools. Opitz is a commercially available part classification and coding system [Chang *et al.*, 1998]. The decision support system is designed to perform coding and classification of parts, generate a list of probable machining operations required, select machine tools and cutting tools, optimize cutting parameters and provide alternative solutions in case of machine breakdown.

Interfacing CAD system with a GT coding system is a common practice for generating feature information for process planning. Nadir *et al.* [1993] presented an automatic GT coding and classification system for machining rotational parts based on a commercial solid modeller. The system allows a CAD system to be interfaced to a CAPP system through GT coding. Lau and Jiang [1998] used a STEP (Standard for the Exchange of Product Model Data) compliant neutral file to connect dissimilar CAD packages to CAPP through a GT coding scheme. Unlike other coding schemes which have a rigid digit length structure, it has a flexible digit length capability that makes it possible to include all the detail of the features in the codes. The features recognition process works in parallel with the GT coding process. The final step is the generation of process plans for machining of the component. This is achieved through a program which is able to interpret the GT codes and generate an optimized process plan for machining of the component. A similar approach is developed by Lau *et al.* [2005] for integrating CAD and CAPP which also contributes to research related to GT-based automated process planning. The benefit of this approach is that the product designs with dissimilar formats from various CAD systems can be interconnected and automatically coded for multiple manufacturing purposes. An expert system development tool, CLIPS (C Language Integrated Production System) is used for developing the process planning function.

The features of the part are sequenced in order to minimise the number of setups and tool changes.

Joshi *et al.* [1994] describes the development of a generic GT shell for process planning. The system is based on a PC based database management system. Variant GT based approach is used to retrieve an existing process plan and generative techniques are used to modify the plan to suit the new part. It is very flexible and customized GT codes can be developed for different parts

Jiang *et al.* [1997] presented an automated procedure for milling of prismatic components using a GT coding scheme. The methodology enables the component coding scheme to be integrated with an expert system for the selection of machining operations, sequencing the machining operations, and the selection of cutting tools. By integrating the proposed GT code and process planning knowledge, the machining facilities can be optimized.

Decision table is another tool used to represent process information. It organises the conditions (IF), actions (THEN) and decision rules in a tabular form. Conditions and actions are placed in rows of the decision table, while decision rules are placed in the columns. When all the conditions in a decision table are met, a decision is taken. The algorithm for implementing the decision table may be written in either some specially developed language or any of the procedural programming languages such as FORTRAN, PASCAL, C, *etc.* Table 2.1 is a sample decision table.

**Table 2.1.** A sample decision table

Conditions	Rules			
	Yes	No	Yes	Yes
Condition-1	Yes	No	Yes	Yes
Condition-2	No	No	Yes	Yes
Condition-3	Yes	Yes	No	No
<b>Actions</b>	X		X	
Action-1		X	X	
Action-2	X			X

CUTTECH (Cutting Technology), a system for selection of cutting tools, speeds, and feeds for machining operations uses both decision tables and algorithms [Barkocy and Zdeblick, 1984]. The knowledge-base comprises machining rules and machine tool and cutting tool data. Rules are applied in descending order of importance to sort a list of tools from the most to the least preferred tools.

HI-MAPP (Hierarchical and Intelligent Manufacturing Automated Process Planner), an automated process planning system uses both decision tables and knowledge-based rules for decision making [Berenji and Khoshnevis, 1986]. The part is represented by a set of form features such as hole, slot, groove, *etc.* The plan generation process starts with an initial feasible plan given as input. It is then expanded incrementally by including the detail. HI-MAPP considers minimization of total machining time.

Kim *et al.* [1996] developed an automatic setup planning method for machining of prismatic parts considering machining of reference faces as well as features concurrently. Decision table is used to determine the machining sequence of reference faces based on part dimension, degree of surface roughness, fixture type and cutting tool. Reference faces and features which can be machined in the same setup are searched and machined together so that number of setups is minimized.

Decision trees, decision tables, and GT codes, often used in traditional CAPP systems, work effectively only for simple decision making processes. The main limitation with the decision trees and decision tables is that they are relatively static in terms of representing the process planning knowledge. These are primarily methods to represent knowledge and are coded line by line in the program. Any modification to the current knowledge would require rewriting of the original program. They lack the ability to automatically acquire knowledge and need longer response time. Moreover, GT code based input is not suited for automated process planning systems, since coding is a manual process. It is both time consuming and prone to error. Another major disadvantage of GT coding based systems is the cost involved in creating and maintaining databases for the part families. Table 2.2 shows some traditional efforts of setup planning highlighting the key points.

**Table 2.2.** Major Setup planning approaches using decision tree, decision table and group technology (GT)

	References	Type of part	Main constraints considered
D E C I S I O N  T R E E  &  T A B L E	Davis and Darbyshire [1984]	Rotational	Precedence relation, resources
	Wysk <i>et al.</i> [1988]	Rotational	Precedence relation, process parameters
	Chitta <i>et al.</i> [1990]	Both rotational and prismatic	Process parameters, machine tool and cutting tool capacities
	Barkocy and Zdeblick [1984]	Both rotational and prismatic	Process parameters, resources
	Berenji and Khoshnevis [1986] Kim <i>et al.</i> [1996]	Prismatic Prismatic	Precedence relations, machining time Surface roughness, part geometry, TAD
G  T	Nadir <i>et al.</i> [1993]	Rotational	Topology, part geometry
	Joshi <i>et al.</i> [1994]	Prismatic	Part geometry, precedence relations
	Jiang <i>et al.</i> [1997]	Prismatic	Precedence relations, cutting tool
	Lau and Jiang [1998]	Prismatic	Part geometry, precedence relations
	Lau <i>et al.</i> [2005]	Prismatic	Part geometry, flexibility

### 2.2.2 Algorithmic and Graph Theoretic Approaches

Algorithms and graphs are powerful mathematical tools that have been used for solving setup planning problems. An algorithm is a sequence of finite logical and mathematical expressions for solving a given problem. A graph is a collection of finite number of vertices and edges. Each edge is identified with a pair of vertices. A setup planning problem can be formulated in terms of graphs. For example, two faces of a part may be represented by two vertices and the tolerance relation between the two faces can be represented by the edge connecting the two vertices. For traversing the required vertices or edges, different algorithms are used. Two common algorithms used for finding the shortest path through a graph are the depth-first-search and the breadth-first-search methods. Both algorithmic and graph theoretic approaches have been used in CAPP for setup planning.

Pande and Walvekar [1990] developed an interactive computer assisted process planning system PRICAPP for machining of prismatic parts used in the production of portable electric tools. The system is capable of feature representation, machine

selection, operation extraction and sequencing, process parameter selection, setup planning and machining time calculation.

Thakar *et al.* [1993] developed an integrated process planning and NC part programming system for machining of rotational components. Standard lathe machine operations such as turning, facing, boring, thread cutting, and drilling can be performed by the system. The process planning module contains databases for machining operations, machine tools, cutting tools, machining parameters, work material, tool material, *etc.* Process plans are generated for machining a component selecting the appropriate operations, machines, tools, and machining parameters from these databases. The NC part programming module takes input from the process planning module and generates part program by retrieving the corresponding part program and modifying it accordingly.

Zhang *et al.* [1995] used a hybrid of heuristic and algorithmic approach for setup planning of prismatic parts. Setups are formed based on TAD (tool approach direction). Bilateral precedence relations among the features arising from geometric relations, datum/reference requirements, feature interaction, and good manufacturing practice are considered to form the machining constraints. These constraints are converted into rules and used for generating the setup plans. An algorithm is developed to find the optimal setup plan with the minimum number of setups. To reduce the size of the problem, features sharing the same geometric and technological attributes are merged as a compound feature, and only promising solutions are searched.

Sarma and Wright [1996] used a graph theoretic approach to minimize the number of setups and tool change for simply fixturable parts in milling. Precedence relations among the machining operations are the main constraint considered. Machining operations are represented as vertices and edges between two vertices represent the precedence relations. An optimal setup plan is generated by sequencing the operations so that none of the precedence constraints are violated. Algorithms are presented for minimizing the number of setups and number of tool changes.

Tailbar [1996] presented an optimal machining operation sequencing method for drilling and milling of prismatic work pieces with an objective to minimize

manufacturing cost. Optimal operation sequences are generated subject to the constraints of number of tool changes, machining cost, machine tool and cutting tool cost, and tool path. Operation sequences are to be evaluated on the basis of a cost model. Basic algorithms used are gradient projection, branch and bound, shortest common super sequence, and threshold accepting method.

Karadkar and Pande [1996] developed a feature based process planning system PRISPLAN for generating CNC codes for machining of prismatic parts. The system has a feature based modeller (FBM) where the user can construct the part model interactively using the part design and manufacturing information. The CAPP module processes the information from the FBM and performs setup generation, operation sequencing, cutter location data generation and CNC code generation.

Marefat and Britanik [1997] developed a case-based process planning approach combining the benefits of both variant and generative CAPP methods. An object-oriented model is used for representing the features of prismatic parts. The plans for machining different types of features are stored in the database. Old feature machining plans are retrieved and modified to fit the features in the part in hand. Then a plan merging method combines the modified feature plans into a global process plan for the part.

Chu *et al.* [2000] presented a process planning methodology called PIPP (Prototype-based Incremental Process Planning). The whole activity of process planning is divided into two stages, creation and modification of process plan prototype. PIPP methodology offers a framework and open architecture in which different kinds of artificial intelligent techniques can be effectively applied and different optimization algorithms and development tools can be integrated easily to build a practical CAPP system.

Lee *et al.* [2001] developed a precedence directed graph to represent the operation precedence constraints for setup planning of turned parts. A searching strategy developed by the authors is used to search through the graph for feasible operation sequences for different setups. These sequences are further optimised with respect to machine change, setup change and tool change costs.

Sadaiah *et al.* [2002] designed a modular generative CAPP system PSG-CAPP for prismatic parts capable of feature extraction, setup formation and operation

sequencing and optimization using an algorithmic approach. Manufacturing constraints considered for operation sequencing and setup planning are TAD, part geometry, feature precedence constraints, cutting forces generated during machining, and feature tolerance relations.

Patil and Pande [2002] developed an advanced process planning system IFPP (intelligent feature-based process planning) for prismatic parts to be machined in CNC machining centres. IFPP consists of two modules. The first module is a feature based modeller (FBM) with a graphical environment for representing the solid model of the part with all the information of the features. The second module is the process planning module AutoPlan which takes feature information from FBM and performs the tasks of setup planning, feature-machining process mapping, tool path planning and finally CNC code generation. The criteria considered for setup planning are TAD, tolerance relations, precedence relations and orientation of the features. In IFPP, Parametric programming is used to generate a feature specific CNC code which makes the code more flexible.

Sormaz and Khoshnevis [2003] proposed an algorithmic approach to generate alternative process plans for machining of prismatic parts. Alternative machining operations are considered for each feature and feature precedence relations are formulated analysing feature interactions. Feature clustering and sequencing are done based on precedence relations. Optimal process plans are searched based on minimum manufacturing cost per unit workpiece.

Gologlu [2004] proposed a heuristic method for operation sequencing for machining of prismatic components. The proposed operation sequencing module is a part of the integrated knowledge-based CAPP system called ProPlanner. Near optimal operation sequences are generated for each setup which is evaluated against minimum machining cost and minimum tool change. A graph theoretic approach is used for representing the feature precedence relations. A tool change minimization algorithm is developed by the authors based on feature precedence relations and maximum use of the same tool for different features. The algorithm not only minimizes tool changes, but also reduces the number of tools used.

**Table 2.3.** Major Setup planning approaches using algorithms and graph theory

References	Type of part	Main constraints considered
Pande and Walvekar [1990]	Prismatic	Part geometry, machining time
Thakar <i>et al.</i> [1993]	Rotational	Process parameters, resources
Qiao <i>et al.</i> [1994]	Prismatic	Precedence relations, tolerance, surface finish
Zhang <i>et al.</i> [1995]	Prismatic	Precedence relations, TAD, tolerance
Sarma and Wright [1996]	Prismatic	Precedence relations, TAD, fixtures
Tailbar [1996]	Prismatic	Optimality, cost, tool path
Karadkar and Pande [1996]	Prismatic	Part geometry, tolerance
Marefat and Britanik [1997]	Prismatic	Part geometry, feature relations
Chu <i>et al.</i> [2000]	Rotational	Part geometry, tolerance, surface finish
Lee <i>et al.</i> [2001]	Rotational	Precedence relations, TAD, and cost factor
Sadaiah <i>et al.</i> [2002]	Prismatic	Precedence relations, TAD, part geometry
Patil and Pande [2002]	Prismatic	Tolerance, Precedence relations, TAD
Sormaz and Khoshnevis [2003]	Prismatic	Precedence relations, manufacturing cost
Gologlu [2004]	Prismatic	Precedence relations, tool change cost
D'souza [2006]	Prismatic	Feature interaction, tool sequence
Lee <i>et al.</i> [2007]	Prismatic	Precedence relations, TAD, part geometry
Rameshbabu and Shunmugam [2009]	Prismatic	TAD, precedence relations, tolerance

D'souza [2006] addressed the issue of selection and optimization of tool sequences in machining where several features are machined in a single setup. Some of these features may be nested leading to feature precedence constraints. Tool sequence selection becomes a complex problem because of the various interactions between features in a setup. A graph based algorithm for selecting the cheapest tool sequence and an algorithm for efficiently machining the features in a setup are described.

Lee *et al.* [2007] developed an algorithm for recognizing composite features for prismatic parts from CAD model and generating process plans based on topological sorting and breadth-first search of graphs. First the composite features are classified based on machining precedence relations and then a recognition algorithm for the composite features is proposed based on orthographic projection.

Rameshbabu and Shunmugam [2009] applied a hybrid of volume subtraction and face adjacency graph approach to recognize manufacturing features from 3-D model data in STEP AP-203 format and generate setup plans using manufacturing

preferences. The feature recognition module can deal with different types of features including intersecting features. The feature data is given as input to the setup planning module and feature clustering, sequencing the feature clusters and selection of datum are performed based on TAD, part stability during machining, and part geometry. Table 2.3 shows some setup planning approaches using algorithms and graph theory.

Attaining the specified tolerances is a crucial factor for the quality as well as functionality of a finished part. Tolerance is considered as the main driving factor in setup planning by many researchers. In these approaches, the precision of the final part is treated as the main criterion for setup planning. Some efforts of setup planning where tolerance is the key concern can be found in the literature.

Dong and Hu [1991] proposed a quantitative approach for generating the optimal process tolerances and evaluating alternative process sequences in process planning. Constrained nonlinear optimization is applied to determine the optimal process tolerances with least production costs. The model is evaluated using the empirical production cost-tolerance data of typical production processes, such as drilling, turning, milling, grinding, and casting. The example used to illustrate the method has shown significant production cost reduction.

Huang and Zhang [1996] used a graph theoretical approach for setup planning of rotational parts. All the features present in the part are grouped into three sets according to their TAD, *i.e.* left, right or both left and right directions. A tolerance graph is constructed by representing each feature as a vertex and the tolerance relation between a pair of features by the edge connecting the vertices. The features which can be machined from both the left and right directions are assigned to one of the two setups, left or right, based on their tightest tolerance relationships with other features. The appropriate datum features are chosen based on the tightest tolerance relations with other features.

Demey *et al.* [1996] developed a prototype software package GEOPS (GEneration van OPspanningen: the generation of setups) for setup planning of mechanical parts. Tolerance and precedence relations among the features are the main constraints considered. The output of the system is the minimum number of

setups needed to machine the part, the machines to be used, the orientations of the workpiece with respect to the machine in each setup, and the sequence of operations to be executed in each setup.

Zhang *et al.* [1996] developed a setup planning system with emphasis on attaining specified tolerances of the features present in the part. Graph theoretical approach is proposed for selection of setups and setup datums, and generation of optimal setup plans based on design tolerance specifications. The paper discusses the importance of setup planning and tolerance control in process planning.

Huang *et al.* [1997] used graphs to represent the tolerance and datum relationships among features. Preliminary setups are formed based on TAD. The problem of identifying optimal setup plan is transformed into a graph search problem. Graphs are used to refine the preliminary setup formation and datum selection. Tolerance relations are used for operation and setup sequencing.

Wu and Chang [1998] proposed a tolerance driven automatic setup planning approach for prismatic parts based on precedence graphs and algorithms. Positional tolerances among the features are used to generate explicit datum for each setup. The optimal plan is a feasible plan with minimum number of setups and results in the most accurate position relationship between features. A specific TAD is assigned to a feature having multiple TADs on the basis of tightest tolerance. The setup planning methodology is implemented using an automatic process planning system called QTC (Quick Turnaround Cell) developed by Kanumury and Chang [1991].

Huang [1998] used an algorithmic and graph based approach for setup planning for machining of rotational parts. The set of features to be machined and their TAD are identified. The geometric tolerance relationships among the different features are represented in the form of a matrix called the adjacency matrix, where each entry in the matrix represents the value of the geometric tolerance between a pair of features. A graph is constructed from the above adjacency matrix. The set of features to be machined in each setup and locating and clamping features for each setup are searched subject to various constraints such as TAD, tolerance, *etc.*

Zhang and Lin [1999] developed a setup planning approach for prismatic parts using hybrid graph theory accompanied by matrix theory. Both dimensional and geometric tolerances are considered and tolerance relations among features are used

as critical constraints. Each feature is considered to be composed of some faces. The faces of the part are represented as vertices and the tolerance information is represented as the edges of the hybrid graph. The faces are grouped into setups based on commonality of TAD, tolerance requirements and machining precedence requirements. Major objectives are to minimize the total no of setups and machine maximum features in the same setup.

Huang and Liu [2000] focussed on an important issue of tolerance analysis. They developed a tolerance normalization method to express different tolerances in a common unit for comparing them. Normalized tolerance is an angle representing the maximum permissible rotation error when locating a component. Smaller the normalized tolerance, tighter is the tolerance between the features. The same authors [2003] focussed on the issue of tolerance analysis in setup planning. Normalized values of different geometric tolerances among the features, *e.g.* parallelism, perpendicularity, angularity, position, concentricity, symmetry, *etc* are considered for comparison. The methodology is explained with an example part where features and their tolerance relations are represented with a tolerance graph.

Zhou *et al.* [2002] are of the view that setup planning methods still lack a proper interface with CAD models. It is essential for setup planning to ensure the precision of the machining processes. Therefore, it is necessary to develop an interface with CAD models, so that the part data file can be obtained directly from the CAD representation. This paper proposes an approach for integrating the setup planning system with a feature-based CAD system. By using an object-oriented approach, PDT (Product Data Translator), the automated extraction of geometry, TAD, and complete tolerance information is achieved for setup planning.

For setup planning of rotational parts, Shunmugam *et al.* [2002] used a feature precedence graph (FPG) followed by a searching strategy that searches through the graph to find the various feasible sequences of machining the features. Precedence constraints, locating constraints, accessibility constraints, and geometric tolerance constraints arising from the inter-relationships among the features are represented by the FPG. The machining sequences are further optimized using genetic algorithm

with respect to feature adjacency, datum/reference requirements and manufacturing preferences.

Huang and Xu [2003] developed a modular integrated setup planning methodology for prismatic parts to generate setups, setup datums and setup sequences where tight tolerance features are to be machined in the same setup. Parallelism and perpendicularity tolerances among the features are considered for feature clustering and setup formation. Objectives incorporated into the setup formation algorithm are minimizing the number of setups and ensuring that the features with tight tolerance relations are machined in the same setup.

Zhang *et al.* [2003] developed an automated setup planning and tolerance decomposition method using directed graph theory. Feature tolerance graph (FTG) is used to represent feature tolerance relationships and datum and machining feature graph (DMG) is used to represent datum and machining feature relationship. Locating error is identified as one of the prime machining errors and mathematical model for locating error is developed that can be used for ascertaining locating precision and improving a setup plan. Tolerance decomposition models are developed and applied to find the allowable locating errors for part tolerance specification.

Kang *et al.* [2003] stressed on interlinking of design and process planning and developed an integrated approach. Emphasis has been put on the representation of tolerance information by using the neutral product data format STEP. A proper data structure to store various types of tolerance and surface finish data has been proposed. This can help CAPP system to extract manufacturing information contained in STEP AP224 file more easily, regardless of the CAD systems used. The authors believe that this framework contributes towards better information flow towards process planning.

Huang *et al.* [2004] emphasized on the important issue of process plan evaluation. Traditionally the process plans are evaluated on trial and error basis which is time consuming and costly. They proposed an innovative process plan evaluation method based on Monte Carlo simulation. The workpiece geometry is represented by a set of discrete points and as the workpiece undergoes a series of machining processes, the spatial changes of the points are observed. The

manufacturing errors such as work holding error, machine tool error, cutting tool error, *etc* are modelled and can be calculated. Virtual inspection is done to check the effect of these errors on dimensional and geometric tolerances of the part. Based on the evaluations of a set of alternative plans, decision can be taken to select the appropriate process plan.

Xu and Huang [2006] differed from most of the previous researchers by stating that automating setup planning does not mean that human intervention is to be removed. The authors are of the view that there is no clear cut definition of optimality of setup plans and a proper method of evaluating it in the literature. A good setup plan should achieve the highest quality in terms of tolerances and surface finish and be of the lowest cost. Optimality is the degree to which the setup plans achieve the same. They suggested a quantitative setup plan evaluation method based on multiple attribute utility analysis and manufacturing error simulation. The proposed method clearly defines optimality of setup plans and systematically evaluates alternative setup plans.

Yao *et al.* [2007] used graph theoretic approach to automatically generate setup plans for non-rotational parts. Part information is represented by a feature and tolerance relationship graph (FTG) and setup information by datum and machining feature relationship graph (DMG). The problem of automating setup planning is formulated as conversion of FTG to DMG based on tolerance analysis and manufacturing resource capability analysis. In addition to above, precedence and fixturing constraints are considered in determining setup plans.

Hebbal and Mehta [2008] developed a methodology for automatic generation of feasible setup plans for prismatic parts and selecting the optimal plan. The objective is to minimize setup time considering fixturing, machining and tool changing time. Tolerance relations among the features, datum requirement and manufacturing resources are the main considerations for setup planning. The features are grouped into four groups, *viz.* primary group independent of machine tool, primary group for a particular machine tool, secondary group and eligible group. The features with tight tolerance relations are put in the eligible group to be machined in the same machine tool, and with the same datum. The pairs of parallel surfaces are machined

using one as datum for the other. Table 2.4 shows some setup planning approaches with emphasis on tolerance achievement.

**Table 2.4.** Major Setup planning approaches using algorithms and graphs with emphasis on tolerance achievement

	References	Type of part	Main constraints considered
T O L E R A N C E	Dong and Hu [1991]	Rotational	Tolerance, production cost
	Huang and Zhang [1996]	Rotational	Tolerance, TAD, datum relations
	Demey <i>et al.</i> [1996]	Prismatic	Tolerance, precedence relations, cost, and part geometry
	Zhang <i>et al.</i> [1996]	Prismatic	Tolerance, datum relations
	Huang <i>et al.</i> [1997]	Rotational	Tolerance control, precedence relations, TAD
	Wu and Chang [1998]	Prismatic	Tolerance, datum relations, TAD
	Huang [1998]	Rotational	Tolerance, part geometry, TAD
	Zhang and Lin [1999]	Prismatic	Positional and geometric tolerance, TAD
	Huang and Liu [2000]	Both rotational and prismatic	Tolerance normalization
	Zhou <i>et al.</i> [2002]	Rotational	Part geometry, TAD, feature precedence
B A S E D  A P P R O A C H E S	Shunmugam <i>et al.</i> [2002]	Rotational	Tolerance, precedence relations, surface finish
	Huang and Liu [2003]	Both rotational and prismatic	Tolerance analysis and normalization
	Huang and Xu [2003]	Prismatic	Tolerance, precedence relations
	Zhang <i>et al.</i> [2003]	Prismatic	Tolerance, precedence relations
	Kang <i>et al.</i> [2003]	Prismatic	Tolerance, part geometry
	Huang <i>et al.</i> [2004]	Prismatic	Tolerance, datum and feature relations
	Xu and Huang [2006]	Prismatic	Tolerance, cost and optimality
	Yao <i>et al.</i> [2007]	Non-rotational	Tolerance, precedence relations, resources
	Hebbal and Mehta [2008]	Prismatic	Tolerance, datum and precedence relations

Many researchers consider fixturing requirements as an integral part of setup planning. To provide a robust and practical solution for setup planning, setup planning has to be integrated with fixture planning by considering setup and fixturing requirements simultaneously. A fixture provides some locating and clamping mechanism to support and maintain the work piece in a particular position in a setup and resist gravity and other operational forces. The purpose of setup and

fixturing is to ensure the stability and precision of the workpiece during machining processes. There are some attempts in the literature to develop setup plans considering fixturing aspect.

Boerma and Kals [1988, 1989] developed a system called FIXES for automatic selection of setups and datum based on feature tolerances for machining of prismatic parts. FIXES is a sub-system of the process planning system PART developed by the authors. The topology of the prismatic part, tolerance relations among features and accuracy are considered for setup planning. A tolerance factor has been developed to compare the different tolerances. The system automatically selects the positioning, clamping and supporting faces for each setup.

Young and Bell [1991] proposed a methodology for integrating technological and geometrical information of the part and fixturing constraints within a product modelling environment for automating setup planning. The method uses machine capability, part geometry, precedence relations and tolerances among the features as the main constraints for setup planning.

Sakurai [1992] used algorithmic and heuristic methods for automating setup planning and fixture design for prismatic parts. Setups are formed on the basis of TAD analysis of the features and some heuristics are applied to find the best locating faces for each setup. Some of the criteria considered for setup planning and fixturing are part geometry, precedence constraints, total restraint of the part during machining, interference checking for fixturing, and minimum part deformation.

Tseng [1999] proposed an approach for fixture design analysis for feature based machining of prismatic parts. The method analyzes the setups and related fixturing requirements in a sequential feature-based machining considering operation precedence requirements. The workpiece shape at an intermediate step and the feature to be cut is given as input to the fixturing analysis module. The output includes locating faces and points, clamping points, and feasible height ranges for locating and clamping devices.

Joneja and Chang [1999] combined setup and fixture planning considering part geometry, precedence constraints and restraint of the machined part. The setup planning module groups the surfaces to be machined into different setups, generates

alternative setup plans, and selects the plan with the minimum number of setups. The fixture planning module decides the clamping method (vise or modular fixture), selects locating, clamping, supporting faces, and checks tool interference. The proposed method has been implemented as a part of an existing automated process planning system called the Quick Turnaround Cell (QTC) developed by Kanumury and Chang [1991].

Kaya and Ozturk [2001] presented an algorithmic approach to develop an integrated system to generate machining operation groups for different setups and fixture configuration layout for each setup. Feature precedence matrix is used to form the setup and machining operation sequence. An algorithm is presented for selecting the locating and clamping positions. Time varying dynamic machining force analysis is carried out to ensure workpiece stability against cutting and clamping forces. Finite element analysis (FEA) technique is used for stability analysis of the workpiece.

Bansal *et al.* [2008] suggested a modular fixture planning system integrated with feature recognition module, setup planning module and tolerance analysis module. The integrated methodology is developed applying the criteria of stability, accessibility and tolerance minimization. An interactive user interface is designed to take direct input from the STEP file about the component geometry for feature recognition. After reconstruction of the part, setups are formed based on TAD, feature tolerance relations, and machine and tool spatial constraints. Acceptable locating points for each setup are searched subject to accessibility, stability, and minimum tolerance criteria.

Stampfer [2009] developed an automated setup and fixture planning method for box-shaped parts. Features to be machined in a setup, setup sequences, and locating and clamping surfaces for each setup can be generated automatically by the proposed system. Setup formation is done based on the tolerance relations among the features. An orientation of the workpiece is searched where maximum number of features can be machined in a particular clamping position. Locating and clamping surfaces are selected based on shape, size, and position of the surfaces.

Adaptability of the setup plans to changing manufacturing environment is an important issue. Setup plans developed prior to actual production may become

infeasible during actual production time due to changes in the conditions on the shop floor. Adaptation to the changing scenario is a crucial factor in this era of lean and agile manufacturing. Traditional software systems for automating setup planning are static in nature and they do not respond to the changes in the situation. The importance of dynamic and adaptable manufacturing software systems is manifold. Table 2.5 shows some setup planning approaches with emphasis on fixturing aspects and adaptability.

Masood and Srihari [1993] developed a rule-based approach to deal with the uncertainties associated with the actual production stage on the shop floor. The shop floor status is monitored using a real-time database. For any change in the status, the system revises the information stored earlier and provides the current status information. The authors used a non-monotonic reasoning strategy that can revise reasoning procedure if conditions are changed at a later point of time.

Usher and Fernandes [1996] proposed a two phase (static and dynamic) process planning concept. The static phase is concerned with the generation of alternative plans without considering the status of the shop floor resources. The dynamic planning phase takes place when a job is released for production to the shop floor considering the availability of the shop floor resources. The result of this second phase is a set of ranked near-optimal alternative plans.

Feng and Zhang [1998] developed a flexible CAPP system suitable for agile manufacturing which is responsive to the user's changing needs. The process planning function is decomposed into various sub-tasks/modules/components. The proposed CAPP system has the capability to generate process plans by assembling the reusable pre-packaged software components. The user can select the software components interactively according to his need for building the process plan.

The primary focus of Wang *et al.* [2003] is on developing a distributed process planning (DPP) method which is adaptive and responsive to the rapid changes in the shop floor. The proposed approach uses a two-layer structure for process planning, supervisory planning and operation planning. The former focuses on product data analysis, machine selection, and machining sequence planning, and the latter considers the detailed working steps of the machining operations inside each setup

plan. The flexibility enabled by the DPP methodology is beneficial to the reconfigurable manufacturing system.

Azab and ElMaraghy [2007] contributed towards a new concept of reconfigurable process planning (RPP) which is a semi-generative process planning approach suitable for agile and reconfigurable manufacturing system (RMS) environment. A mathematical model for reconfiguring macro-level process plans has been presented. The approach provides much smaller solution space and less number of constraints. The authors further extended the proposed reconfigurable process planning approach [2007]. A genuine reconfiguration of process plans to optimize the scope, extent, and cost of reconfiguration is achieved using an integer programming model.

**Table 2.5.** Major Setup planning approaches using algorithms and graphs with emphasis on fixturing aspects and adaptability

	References	Type of part	Main constraints considered
S E T U P & F I X T U R I N G	Boerma and Kals [1988, 1989]	Prismatic	Topology, geometric relations, positional accuracy
	Young and Bell [1991]	Prismatic	Fixtures, precedence relations, tolerances
	Sakurai [1992]	Prismatic	Fixtures, precedence relations, forces
	Tseng [1999]	Prismatic	Datum, TAD, part geometry
	Joneja and Chang [1999]	Prismatic	Geometry and restraint of part, and precedence relations
	Kaya and Ozturk [2001]	Prismatic	Fixtures, dynamic forces, tolerance
	Bansal <i>et al.</i> [2008]	Prismatic	Fixtures, tolerance, part stability
	Stampfer [2009]	Prismatic	Fixtures, tolerance, datum
A D A P T A B I L I T Y	Masood and Srihari [1993]	Prismatic	Uncertainty, resources, part geometry
	Usher and Fernandes [1996]	Prismatic	Resources, precedence relations
	Feng and Zhang [1998]	Prismatic	Agility, precedence relations
	Wang <i>et al.</i> [2003]	Prismatic	Feature interaction, precedence relations, resources
	Azab and ElMaraghy [2007]	Prismatic	Agility and reconfigurability
	Cai <i>et al.</i> [2008]	Prismatic	Machines, TAD, tool orientation space
	Kannan and Saha [2009]	Prismatic	Machines, reconfigurability, precedence constraints

Cai *et al.* [2008] developed a methodology for setup planning of prismatic parts which is adaptable to different multi-axis machines. A kinematic model for tool accessibility is proposed to generate the feasible tool movement space for different multi-axis machines. Initially, setups are formed based on TAD for a 3-axis machine which becomes the input for other machines of 4-axis and 5-axis type. Number of setups for the same part can be reduced with 4-axis, 5-axis machines, as some setups can be merged with more options for tool accessibility in the multi-axis machines.

Kannan and Saha [2009] proposed a generic setup planning method for prismatic parts for reconfigurable machine tools. Reconfigurable machine tools play an important role in dynamic and adaptable manufacturing systems. An extended hybrid graph theory is used to represent the part and feature relations. From the feature-based CAD data, machining features are grouped according to their TAD. These feature groups are sequenced for a given part orientation. A case study is presented to demonstrate the applicability of developed generic setup planning method.

Approaches based on algorithms and graphs have been reported to give good and accurate results. However, there are limitations of these approaches. They are inflexible particularly for new situations. For example, if there is a change in the manufacturing environment, any modification of the current methodology would require rewriting of the original program. Moreover, for a complex problem, the size of the program becomes large and may need large computing resources.

### **2.3 Approaches based on Artificial Intelligence and Soft Computing Techniques**

The traditional approaches such as algorithms and graphs, decision trees, and decision tables suffer from various shortcomings. They are inflexible and lack the necessary intelligence to automatically acquire knowledge. To overcome some of these limitations, approaches based on artificial intelligence (AI) and soft computing techniques are explored by researchers. In the recent years, many researchers have incorporated AI and soft computing in setup planning and process planning. AI is defined as the simulation of human intelligence on a machine, so as to make the

machine efficient to identify and use the right piece of knowledge at a given step of solving a problem [Konar, 2000]. Generally, problems for which straightforward mathematical/logical algorithms are not readily available and which can be solved by intuitive approach only, are called AI problems. Expert systems, natural language processing, image recognition, and robotics are some of the application areas of AI. Soft computing according to Prof. Zadeh, is “an emerging approach to computing, which parallels the remarkable ability of human mind to reason and learn in an environment of uncertainty and imprecision” [Jang *et al.*, 1997]. Soft computing refers to a collection of tools and techniques which can model and analyze complex problems. Earlier computational approaches could model and precisely analyze only relatively simple problems. More complex problems arising in psychology, philosophy, medicine, computer science, engineering and similar fields often remained intractable to conventional mathematical and analytical methods. These problems are better solved by soft computing techniques. Unlike conventional methodologies (hard computing techniques), soft computing techniques are tolerant of imprecision, uncertainty and partial truth. They do not suffer from inflexibility of conventional algorithmic approaches. Soft computing covers a number of techniques such as artificial neural networks (ANN), fuzzy logic, evolutionary algorithms such as genetic algorithm (GA), simulated annealing (SA), ant colony optimization (ACO), particle swarm optimization (PSO), *etc.* These methods have the potentials to deal with highly non-linear, multi dimensional and complex engineering problems. The application of soft computing techniques is increasing with successful applications in different areas like engineering design, optimization, manufacturing system, process control, simulation and communication systems, *etc.* In the following subsections, a brief review of the application of AI and soft computing techniques in setup planning is presented.

### **2.3.1 Expert System based Approaches**

An expert system is an AI tool used to solve problems that normally require human intelligence. Implementation strategies for different problem solution methods should be general enough to capture knowledge from different sources and simple enough to provide an easily maintainable environment. Expert systems have been the most commonly adopted implementation strategy among the CAPP

developers. They have been used for setup planning in CAPP for their ability of reasoning, collection and representation of large amount of knowledge, and explicit inference route. The modular nature of expert systems makes them easier to encapsulate knowledge and expand them by incremental development. Expert systems should be flexible because facts and rules in an expert system require constant updating. As new technology, equipment, and processes become available, the most effective way to manufacture a particular part also changes. An expert system stores knowledge in a special manner so that it is possible to add, delete, and modify knowledge in the knowledge-base without recoding the program. They can be readily adapted to the changing manufacturing environments by modifying the existing rules in the knowledge-base or by introduction of new rules. Separation of control knowledge or inference engine from the knowledge-base gives added flexibility to the expert systems. In general, expert system is ideally suited when the problem cannot be well defined analytically, the number of alternative solutions is large, the domain knowledge is vast, and relevant knowledge needs to be used selectively. A number of examples of application of expert system to engineering problems are found in Pham [1988]. A background of expert systems is provided in Section 3.2, Chapter 3.

The use of expert system in process planning can be traced back to GARI, a knowledge-based system for planning the sequence of machining cuts for mechanical parts [Descotte and Latombe, 1981]. Machining knowledge, feature description, and dimensional and geometrical relations among features are represented as production rules in the knowledge-base. The left hand side of a rule is a set of conditions about the part to be manufactured, and the available machines. The right hand side of the rule is a set of actions to be taken, in the event the rule is applicable. Under specified conditions, each rule provides the system with a piece of advice, which can be used by the planner for machining. Parts to be machined are described as sets of interrelated features such as faces, bores, grooves, holes, and notches. TOM (Technostructure Of Machining) is another expert system for hole making process [Matsushima *et al.*, 1982]. TOM uses variant planning approach and backward chaining mechanism to generate a machining sequence for drilling holes.

Two expert process planning systems for machining of symmetric rotational components are EXCAP (Expert Computer-Aided Process-Planning) [Davis and Darbyshire, 1984] and PROPLAN (Process Planner) [Philips *et al.*, 1984]. In EXCAP, Knowledge is represented as production rules. Backward chaining logic is used for decision making and generating multiple sequences of operations for machining the component. In backward chaining logic, the goal is known and the THEN parts of the rules are searched to find a matching for the goal. Forward and backward chaining decision logic is discussed in Section 3.2, Chapter 3. PROPLAN uses a simple AI approach of travelling through a graph from initial state to goal state node. It stores the intermediate work piece forms as nodes of the graph and the machining operation as the connecting arc. These are used for decision making about the machining sequences. The knowledge-base consists of production rules on various aspects of machine tools, selection of machining parameters, *etc.* SIPP (Semi Intelligent Process Planning) [Nau and Chang, 1985] and HI-MAPP (Hierarchical and Intelligent Manufacturing Automated Process Planner) [Berenji and Khoshnevis, 1986] are two expert generative process planning systems for machined parts.

Some important reviews towards the use of expert systems in process planning are found in Gupta and Ghosh [1988] and Gupta [1990]. Gupta and Ghosh [1988] surveyed the use of expert systems in several manufacturing applications. Detail of problem definition, implementation scheme, and special features of eight expert process planning systems can be found in the survey. Gupta [1990] emphasised on the need for an expert system approach in process planning. The important features and limitations of the various reported process planning systems are presented, with respect to their part design input scheme, knowledge-base representation, and the control strategy.

Joshi *et al.* [1988] discussed a general strategy for applying solid models to process planning under an expert system framework. The authors developed an expert system to generate setups and operation sequencing for machining of prismatic parts. Production rules are used to establish precedence relations among different machining operations on features. Datum and reference information of the features can be extracted from a solid model of the part. Machining operations are

assigned to different setups based on TAD, resting face, datum requirements, and machine capability. Precedence rules are used to determine the sequence of operations within each setup.

Wang and Wysk [1988] used an expert system based approach for determining the operation sequence and setup formation in setup planning. Four types of constraints are mainly considered, *viz.* operation precedence constraint, part geometry constraint, tooling constraint, and geometric tolerance constraint. A set of production rules has been developed to describe each of the constraints and used to determine the sequence of operation within a setup. Setups are formed based on geometric tolerance relationships among the features in order to obtain the tolerance requirements specified in the part design.

Ferreira and Liu [1988] developed a rule based expert system for automatic generation of workpiece orientation for a setup for machining of prismatic parts. Given the workpiece and machining operation information, and machine specification as input, the system can generate proper workpiece orientation for a setup with respect to the machine's coordinate system. The system has the capacity to reason with the geometrical and spatial relationship of the workpiece with the machine tool with the help of a set of rules.

Ssemakula and Rangachar [1989] stated that the important factors influencing operation sequence for machining a component are the part geometry, geometrical and dimensional tolerances of the features, the available machine tools, cutting tools, and the cutting forces. An expert system SEQUENCE is developed by the authors for sequencing of machining operations. The ultimate objective of the system is to minimize the cost of production without sacrificing the quality of the product.

Prabhu *et al.* [1990] developed a rule based expert system EXPLAN for computer assisted process planning of rotational components. OPS5PLUS shell is used to develop EXPLAN and process planning knowledge is represented in the form of production rules.

Gupta *et al.* [1992] developed a rule-based CAPP system for prismatic parts with the capabilities of machine tool selection, setup planning, tool selection, and operation sequencing. The component geometry can be described interactively by

the user in terms of its shape and features to be machined using a CAD interface. Feature precedence relation and feature interaction are considered for setup planning and operation sequencing.

An object oriented approach is used by Gu and Zhang [1993] for automatic generation of the machining operation sequence in a setup for machining of prismatic parts. The system consists of three modules; product module, manufacturing facility module, and the process planner. The process planner uses a multi-level hierarchical planning approach that consists of four levels; cell level, machine level, fixture level, and tool level. It integrates complete information and associated knowledge about all the three modules which enhances information exchange among the modules and makes the system highly integrated.

Pande and Desai [1995] developed an expert system EXTURN for process planning of rotational parts machined on single spindle automats. EXTURN contains a graphical feature modeller (GFM) and a process planning module. GFM is used for graphical display, synthesis of the part into features, and dimensioning with tolerances. It creates a part file containing the information of the features of the part. The process planning module takes this part information as input and performs the tasks of extraction, sequencing and grouping of machining operations, tool selection and process plan generation.

Sabourin and Villeneuve [1996] used a combination of expert system and constraint programming based approach for setup generation for machining of prismatic parts. The input for setup generation is obtained from the feature based design of the part modelled in CATIA, a CAD system. Setups are formed based on the technological and topological relationships between features, kinematic constraints, and the type of work holder. The features that can be machined in the same setup are determined along with the sequence of operations within the setup based on manufacturing constraints. The methodology is implemented as an expert system named OMEGA (Outil Multi-Expertise en Gamme Automatique (automatic process planning multi-expert system)).

Kim *et al.* [1996] used a rule based expert system shell EXSYS (Expert System Shell) for automatic generation of setup plans for prismatic parts implementing machining of reference surfaces and machining of features concurrently. Machining

operation sequence is determined on the basis of part dimension, degree of surface roughness, fixture type, cutting tool capacity and setup planning knowledge. Reference surfaces and features which can be machined in one setup are searched and machined together so that number of setups is minimized.

Sormaz and Khoshnevis [1996] used a hybrid of a heuristic method and another AI technique, state space search for clustering of processes and finding optimum process sequences for machining of prismatic parts. Process clustering is based on the use of the same resources for several features for saving cost. Process sequencing procedure is based on the best-first state search heuristic algorithm. Machining time and cost for each stage of machining can be calculated and an evaluation function is formulated subjected to the geometrical constraints, technological constraints (power consumed, cutting force, vibration, deformation) and economical constraints.

Kim *et al.* [1998] used a combined expert system and mathematical programming based approach for setup planning for prismatic parts. Rules have been used to generate feature precedence constraints based on datum and reference requirements. A mathematical programming model was used for grouping of machining operations into setups based on TAD and tool commonality to minimize the number of tool changes. Operation sequencing is done subject to the precedence constraints.

Jiang *et al.* [1999] developed an expert system, APPS (Automatic Process Planning System) for machining of prismatic parts. The APPS extracts form features represented by a GT coding system and automatically generates optimal process plans. Some more knowledge-based process planning systems can be found in the References [Eskicioglu, 1992; Shooshtarian *et al.*, 1993; Qiao *et al.*, 1994; Younis and Wahab, 1997; Raman and Marefat, 2004].

Park [2003] proposed a three-phase modelling methodology for knowledge extraction for process planning. By making use of the three-phase modelling, four knowledge elements are derived; facts from the object model, constraints from the functional model, and way of thinking and rules from the dynamic model. The way of thinking is a logical procedure for quickly decreasing the solution space and rules

are the key parameters that control the way of thinking. The proposed methodology is applied to the process planning of hole making.

Gologlu [2004] proposed a knowledge-based methodology for automatic generation of setups considering fixturing constraints. Part geometry, tolerance and dimensions of the part, and feature interaction are used to form the precedence constraints among the features. Setup clusters were formed based on TAD and precedence relations. Conceptual fixture design is performed and locating surfaces for the setups are identified.

Deb and Ghosh [2007] used an expert system based methodology for automating setup planning for rotational parts and implemented it using an expert system shell. A set of rules are used for clustering machining operations into setups based on TAD and feature tolerance relationship. Another set of rules are used to generate feature precedence constraints, determine operation sequence in each setup, and select locating and clamping features for each setup.

An important contribution for sequencing of interacting machining features in setup planning is proposed by Liu and Wang [2007]. The authors proposed a hybrid approach using both knowledge-based rules and geometric reasoning rules for sequencing interacting features. A set of knowledge-based rules are formulated to establish the precedence constraints among the features. A feature may have manufacturing interactions with other features which produce hard constraints that must be satisfied. It may have soft constraints regarding quality, cost, *etc.* Features are grouped into setups based on TAD and geometric reasoning rules are used to sequence the features within a setup. Another effort on sequencing of interacting features in a setup using knowledge-based approach is found in Lin *et al.* [1998]. Table 2.6 shows some expert system based setup planning efforts.

The application of knowledge-based expert systems offers number of advantages as explained in the beginning of Section 2.3.1. The expert systems, however, suffer from some weaknesses. It is restricted to the fields where expert knowledge is available and it is unable to infer when information provided is incomplete. It can not automatically acquire knowledge. The new knowledge must be incorporated into the expert system by specifying it in explicit rule format.

**Table 2.6.** Major Setup planning approaches using expert systems

	References	Type of part	Main constraints considered
E X P E R T	Descotte and Latombe [1981]	Both rotational and prismatic	Feature relations, part geometry
	Matsushima <i>et al.</i> [1982]	Rotational	Feature relations, tools
S Y S T E M	Davis and Darbyshire [1984]	Rotational	Precedence relation, resources
	Philips <i>et al.</i> [1984]	Rotational	Part geometry, process parameters
B A S E D	Nau and Chang [1985]	Both rotational and prismatic	Part geometry, precedence relations
	Berenji and Khoshnevis [1986]	Prismatic	Precedence relations, machining time
A P P R O A C H	Joshi <i>et al.</i> [1988]	Prismatic	TAD, datum, precedence relations
	Wang and Wysk [1988]	Prismatic	TAD, machines, precedence relations
H E S	Ferreira and Liu [1988]	Prismatic	Machine coordinate, part geometry
	Ssemakula and Rangachar [1989]	Prismatic	Part geometry, precedence relations, tolerance, tools
P R O C E S S	Prabhu <i>et al.</i> [1990]	Rotational	Part geometry, tolerance, cost
	Gupta <i>et al.</i> [1992]	Prismatic	Part geometry, resources, cost
P L A N N I N G	Gu and Zhang [1993]	Prismatic	Part geometry, TAD, feature interactions
	Pande and Desai [1995]	Rotational	Part geometry, tolerance
S E T U P	Sabourin and Villeneuve [1996]	Prismatic	Process parameters, tolerance, fixtures
	Kim <i>et al.</i> [1996]	Prismatic	Surface roughness, part geometry, TAD
P L A N N I N G	Sormaz and Khoshnevis [1996]	Prismatic	Feature interaction, force, tool
	Kim <i>et al.</i> [1998]	Prismatic	Precedence relations, TAD, tool
S E T U P	Lin <i>et al.</i> [1998]	Prismatic	Precedence relations, tolerance, TAD
	Jiang <i>et al.</i> [1999]	Prismatic	Precedence relations, TAD, optimality
P L A N N I N G	Park [2003]	Both rotational and prismatic	Precedence relations and tolerance
	Gologlu [2004]	Prismatic	Precedence relations, fixtures, datum
S E T U P	Deb and Ghosh [2007]	Rotational	Precedence relations, tolerance, TAD
	Liu and Wang [2007]	Prismatic	Feature interactions and precedence relations

### 2.3.2 Artificial Neural Network (ANN) based Approaches

Another AI technique used for setup planning is artificial neural network (ANN). An artificial neural network is an information-processing model that is inspired by the way human brain process information. ANN having artificial

intelligence behaves like a biological neural system. In ANN, various nodes called neurons are interconnected in the network. These can be used for finding out the relationship between input and output variables. Different types of networks are used for finding out the relation between input and output variables. ANN can learn the complex relationships among the data and it is very useful in modelling complex processes for which mathematical modelling is difficult. Neural networks, with their remarkable ability to derive meaning from complicated or imprecise data can be used to extract patterns and detect trends that are too complex to be noticed by either human or other techniques. A trained neural network can be considered as an expert and used to provide predictions for unseen situations. ANN approaches offer number of advantages such as capability to automatically acquire knowledge from examples, higher processing speed, *etc.* Moreover, it is capable of adapting to changing environment through retraining.

Chen and LeClair [1993, 1994] used artificial neural network approach for setup generation and feature sequencing for machining of prismatic parts. An unstructured ANN was used for clustering the features into setups based on TAD of the features and commonality of cutting tools. The input pattern to the neural network consists of all the features of the part along with their TAD, and the set of tools needed for processing each feature. After running the neural network, the features are automatically clustered into a number of setups in a way to minimise the number of tool changes. Intersecting and nonintersecting features within a setup are identified for feature sequencing. An optimal-tool-sequence algorithm is introduced to find the best machining sequence of the features in a setup.

Mei *et al.* [1995] used ANN approach for automatic selection of datum in setup planning of rotational parts. In this work, a three layer back propagation neural network (with one hidden layer) is used to select the surfaces for locating and clamping for each setup. The input to the neural network consists of the geometry of the part, and the tolerance specifications between the different part surfaces. The output of the network gives the surfaces selected for locating and clamping. The input data for datum selection, namely the part geometry and tolerance specifications have to be entered manually by the user.

Chen *et al.* [1998] used a hybrid of Hopfield neural net and simulated annealing for setup planning of prismatic parts. The feature sequencing problem is mapped to the well-known travelling salesman problem (TSP) by considering each feature as a city and the setup time (setup, fixturing and tool change time) as the distance between the cities. TSP is a combinatorial optimization problem studied in operational research and computer science. Given a list of cities and their pair wise distances, the task is to find a shortest possible tour that visits each city exactly once. The precedence relations and the tolerance relations among the features are considered as constraints and the feature sequencing problem is solved using Hopfield neural network approach. An algorithm based on simulated annealing was adopted to search for the minimum energy state of the net while avoiding the local minima. The feature sequence obtained aims at minimising the number of setups and tool changes while ensuring no violation of feature precedence and tolerance relations. After determining the feature sequence, the setups are generated based on common tool approach directions.

Ming and Mak [2000] and Chang and Angkasith [2001] also used a similar approach of mapping setup planning problem to the TSP problem. Ming and Mak [2000] used self-organising neural networks and Hopfield neural networks to solve the setup planning problem of prismatic parts. Kohonen self-organising neural network is used to group the machining operations into setups considering TAD, feature precedence relationships, tolerance relationships, and fixturing constraints. The input patterns to the Kohonen neural network consist of all the machining operations needed to machine the part along with the relevant information on each operation. After running the neural network, the operations are automatically grouped into a number of setups. Once the generation of setups is complete, the Hopfield neural network is used to solve the problem of determining the operation sequence within a setup and the setup sequence. Each machining operation is considered as a city and the constraints among the operations are the distances between the cities. A similar approach is adopted for setup sequencing. Chang and Angkasith [2001] used a Hopfield neural networks based approach for operation sequencing in setup planning for prismatic parts. For a given part, the possible part

orientations and feature accessibilities of each part orientation are identified. Then the part orientations that can machine all the manufacturing features with a minimal number of changes are determined and the features are clustered accordingly. The constraints considered are feature precedence relationships, tool commonality and TAD. The tool travel distances between features of the above part orientations are calculated and expressed in the form of a matrix. Then by considering each feature within a setup as a city and the tool travel distance between the features as the distance between the cities, the problem of sequencing the features is mapped onto the TSP and solved using the Hopfield neural network. The output from the Hopfield neural network is the machining operation sequence with the minimum tool travel distance between features.

Deb and Ghosh [2005] developed an intelligent CAPP system to machine rotationally symmetrical parts. Back propagation ANN technique is used to automatically select the machining operations to machine the part and an expert system is used for setup planning. A heuristic approach is applied to build a set of rules representing the prior domain knowledge and the rules are used to pre-structure the input to the ANN. The input variables to the ANN are the feature type, their dimensions, tolerances and surface finish. Output is the set of possible operation sequences. The expert system for automatic setup plan generation takes the information on part features and selected machining operations as input. CLIPS rule based expert system shell is used for setup formation and datum selection.

Amaitik and Kilic [2007] used a hybrid of ANN, fuzzy logic and rule based approach for the development a of STEP-based intelligent CAPP system. Focus of the work is the integration between CAD and process planning using STEP. The system maps a STEP AP224 XML data file with the process planning module. ANN is used to select machining operations, cutting tools, and machine tools. Fuzzy logic is used to select machining parameters for machining operations, cutting tool materials, and workpiece material combinations. Setup planning is carried out based on a number of machining rules embedded in a setup planning algorithm. TAD and feature precedence relations are considered for feature grouping and operation sequencing. The use of the hybrid approach has enabled the development of a flexible CAPP system. Table 2.7 shows some ANN based setup planning efforts.

**Table 2.7.** Major Setup planning approaches using artificial neural networks (ANN)

	References	Type of part	Main constraints considered
A	Chen and LeClair [1993, 1994]	Prismatic	TAD, precedence relations, tool capability
	Mei <i>et al.</i> [1995]	Rotational	Datum, tolerance, part geometry
N	Chen <i>et al.</i> [1998]	Prismatic	Precedence relations, TAD
	Ming and Mak [2000]	Prismatic	Precedence relations, tolerance, fixtures
N	Chang and Angkasith [2001]	Prismatic	Precedence relations, TAD, tools
	Deb and Ghosh [2005]	Rotational	Precedence relations, TAD, tolerance
	Amaitik and Kilic [2007]	Prismatic	TAD, tolerance, surface finish, part geometry

The approaches based on neural networks, however, have some shortcomings. The requirement of huge amount of training and testing data, the presence of the outliers and lack of one well-established standard method of training of neural network poses a challenge for the researchers. Moreover, neural networks provide no explanation of the rationale behind their inference procedure. Their lack of explicitly stated rules and vagueness in knowledge representation leads to a black box nature.

### 2.3.3 Application of Evolutionary Algorithms

Setup planning is a discrete optimization problem involving simultaneous optimization of several objectives. Usually there is no single optimal solution, rather a set of alternative solutions. A combinatorial optimization problem cannot be solved by deterministic algorithms or the traditional optimization methods as they are either too time consuming or too difficult to find an acceptable solution. Evolutionary algorithms like genetic algorithm (GA), simulated annealing (SA), particle swarm optimization (PSO), ant colony optimization (ACO), *etc.* seem to be suited for this kind of problem because they process a set of feasible solutions in parallel, and search for multiple near optimal solutions. Evolutionary algorithms are stochastic search methods that mimic the metaphor of natural biological evolution and the social behaviour of species. The behaviour of such species is guided by learning, adaptation, and evolution. In general, evolutionary algorithms share a common approach for their application to a given problem. The problem first requires some representation to suit each method. Then, the evolutionary search

algorithm is applied iteratively to arrive at a near-optimum solution. Evolutionary algorithms are best suited to solve inherently intractable problems called NP-hard problems. NP (Nondeterministic Polynomial-time)-hard problems are combinatorial optimization problems for which no exact solution algorithm is possible that would lead to a simple or rapid solution. Instead, the only way to find an optimal solution is a computationally-intensive, exhaustive analyses in which all possible outcomes are tested. Finding the optimal setup planning and process planning solutions are considered as NP-hard problems.

The first evolutionary-based technique introduced in the literature was the GA. GA was developed based on the Darwinian principle of the 'survival of the fittest' and the natural process of evolution through reproduction. GA is a search strategy ideally suited to parallel computing and most effectively applied to problems in which small change result in nonlinear behaviour in the solution space. GA can search very large solution space using probabilistic transition rules instead of deterministic ones. A solution to a given problem is represented in the form of a string, called 'chromosome', consisting of a set of elements, called 'genes', that represent the solution variables. GA works with a random population of solutions (chromosomes). The fitness of each chromosome is determined by evaluating it against an objective function. To simulate the natural survival of the fittest process, best chromosomes exchange information (through crossover or mutation operators) to produce offspring chromosomes. The offspring solutions are then evaluated. The process is continued for a large number of generations to obtain a near optimum solution.

Vancza and Markus [1996] proposed a feature based process planning model which can reason using expert's knowledge over a detailed model of the part, the manufacturing processes and resources. Expert knowledge captured in the form of frames and rules is used for building up a search space of feasible process plans. GA is used to find the optimal process plan based on minimum manufacturing cost by simultaneously considering the feasible process plan alternatives.

Zhang *et al.* [1997] developed a GA based approach for finding optimal process plan for prismatic parts machined in a conventional job shop. The process planning function for a part is modelled by simultaneously considering the selection of

machining operations, machine tools, cutting tools, and operations sequence. Fixturing requirement, datum requirement, and good manufacturing practice are considered to determine the precedence relationships between features. The developed GA based approach is able to achieve a near-optimal process plan through specially designed crossover and mutation operators. Flexible criteria are provided for plan evaluation based on minimization of total machining cost.

Dereli and Filiz [1999] developed a process planning system for prismatic parts, called OPPS-PRI (Optimised Process Planning System for Prismatic parts). GA is used for optimising the process plans. The different modules of the system are modelling and feature recogniser module, process planning module, optimization module, design for manufacturing module, and CAPP/CAM interface module. In this work, three GA-based methods are developed for optimizing sequence of operations, tool positions and optimization of cutting parameters. They can be used as stand-alone systems or as integrated optimization modules within OPPS-PRI.

Shunmugam *et al.* [2000] proposed a GA based methodology to find the optimum process parameters (number of passes, speed, feed, and depth of cut for each pass) in multi-pass face milling operation. Objective set is the minimum total production cost subjected to the constraints of allowable speed and feed, tool wear, dimensional accuracy, surface finish, machine tool capability, *etc.* Cost of a single pass is the sum of the machining cost, tool cost, tool change cost, and idle tool travel cost. The authors reported that the proposed GA based method yields lower or equal value of total production cost obtained by integer programming and dynamic programming. The developed module can be integrated with CAPP system for selection of optimum process parameters for machining.

For setup planning of rotational parts, Shunmugam *et al.* [2002] developed a preliminary planning module for operation sequencing at the form feature level. Feature precedence graph (FPG) is used to represent feature information. A searching strategy that searches through the graph is applied to find the various feasible sequences of machining the features subjected to the constraints of feature precedence and tolerance, locating constraints, accessibility constraints, surface

finish, *etc.* The machining sequences are further optimised using GA with respect to feature adjacency, datum/reference requirements and manufacturing preferences.

An important contribution by Li *et al.* [2005] is a web based CAPP optimization module which can optimize the selection of machining resources, setup plans and sequencing of machining operations to achieve optimized process plans for prismatic parts. The system is independent of the operating system, and can be used by geographically distributed manufacturers through Web and Java technology. The Web based system provides a convenient platform for users to view and evaluate a design model effectively. A combined Tabu Search (TS), Simulated Annealing (SA) and GA based approach is used for optimization process. Objective is to minimize total machining cost comprising cost of machines and tools, setup cost, and machine change, tool change and setup change costs. A similar approach is developed by Li *et al.* [2005] for distributed manufacturing environment. A GA-based methodology for finding optimum process plans in distributed manufacturing environment for geographically dispersed machines and tools is developed. It is capable of performing multi-objective optimization based on minimum production cost or minimum processing time.

Bo *et al.* [2006] used GA to optimize process route for machining prismatic parts. Ordering (precedence) constraint, clustering constraint (grouping features based on similarities of geometry, tool, and TAD), and minimum machining time are the manufacturing constraints considered. Natural number is adopted in coding strategy, and selection, crossover and mutation operators are executed on the population to search the optimal process route in the global feasible space.

Despite its benefits, GA requires long processing time for a near optimum solution to evolve. In an attempt to reduce processing time and improve the quality of solutions, other evolutionary algorithms have been introduced during the past decades. Particle swarm optimization (PSO) was developed by Kennedy and Eberhart [1995] and PSO is inspired by the social behaviour of a flock of migrating birds trying to reach an unknown destination. In PSO, each solution is a 'bird' in the flock and is referred to as a 'particle'. A particle is analogous to a chromosome in GA. Similar to PSO, another evolutionary method is ant colony optimization (ACO). ACO is a population based, general search technique which is inspired by the

pheromone trail laying behaviour of real ant colonies for the solution of difficult combinatorial problems. ACO was developed by Dorigo et al. [1996] based on the fact that ants are able to find the shortest route between their nest and a source of food. This is done using pheromone trails, which ants deposit whenever they travel, as a form of indirect communication. Some of the PSO and ACO based setup planning and process planning efforts are discussed hereunder.

Mohammed *et al.* [2008] explored the application of PSO to solve shortest path (SP) routing problems. Some important applications of the SP problem include operation sequencing in setup planning in machining, path planning in robotic systems, vehicle routing in transportation systems, and traffic routing in communication networks, *etc.* The shortest path (SP) problem concerns with finding the shortest path from a specific origin to a specified destination in a given network while minimizing the total cost associated with the path. It is observed that the performance of the proposed PSO algorithm surpasses those of recently reported genetic algorithm based approaches for this problem.

Guo *et al.* [2009a] developed an integrated process planning and scheduling (IPPS) methodology using a modified PSO technique. The authors investigated the applications of PSO into the intractable operation sequencing problem in setup planning. Each machining operation is modelled as a particle with information on TAD, machine tool, and cutting tool. Precedence constraints among the features are formed based on fixture interaction, tool interaction, datum interaction, *etc.* A comparative study among the modified PSO, GA and SA is presented highlighting their different characteristics. A similar methodology is proposed by Guo *et al.* [2009b] using PSO for optimization of operation sequences and setup determination for five-axis prismatic parts. Features with different tool access directions can be machined in the same setup with the same datum in five-axis machining. Operation sequencing is modelled as a combinatorial optimization problem and PSO is used as the solution technique.

An optimization technique based on ant colony algorithm was proposed by Vijaykumar *et al.* [2003] for solving multi-pass turning optimization problems. Optimum cutting parameters including cutting speed, feed rate, depth of cut and

number of rough cuts are obtained by minimizing the unit production cost. Various constraints considered are parameter bounds, tool life constraint, operating constraints consisting of surface finish, force and power required chip–tool interface temperature constraint, and roughing and finishing parameter relations.

Lv and Zhu [2005] defined process planning as a path searching problem and ACO is used to find the optimal path using the workshop resources with minimum time and cost. In the newly developed ACO, real distances are used to guide the ants in place of local pheromone deposits. The state of a work piece is defined by the states of its features. Each feature can have four states, *viz.* stock, rough, semi-finish, and finish. Machining process can be defined as a state transition from stock state to product state. Objective function is to search for a path to reach finish state from stock state with minimum time and cost.

Krishna and Rao [2006] used ACO to find the optimum operation sequence in a setup for machining of prismatic parts. A part is described as an assembly of form features with geometric specifications, tolerances and surface finish. Various feasibility constraints such as locating constraint, geometric tolerance, accessibility, datum requirements are considered for operation sequencing in a setup. A precedence cost matrix is generated for any pair of features based on the relative costs corresponding to change of machining parameters, tool change, setup change, and machine change. Table 2.8 shows some setup planning efforts using various evolutionary techniques.

The difficulties associated with using mathematical optimization techniques to large scale engineering problems have contributed to the development of alternative solutions. To overcome these difficulties, researchers have proposed evolutionary-based algorithms for searching near-optimum solutions. Some researchers suggest that multi-objective search and optimization is an area where evolutionary algorithms do better than other optimization methods.

**Table 2.8.** Major Setup planning approaches using evolutionary algorithms

	References	Type of part	Main constraints considered
G E N E T I C  A L G O R I T H M	Vancza and Markus [1996]	Prismatic	Feature relations, resources, cost
	Zhang <i>et al.</i> [1997]	Prismatic	Precedence relations, time, cost
	Dereli and Filiz [1999]	Prismatic	Feature interaction, TAD, part geometry
	Shunmugam <i>et al.</i> [2000]	Prismatic	Cutting force, surface finish, tool capacity
	Shunmugam <i>et al.</i> [2002]	Rotational	Tolerance, precedence relations, surface finish
	Li <i>et al.</i> [2005]	Prismatic	Resources, machining cost
	Li <i>et al.</i> [2005]	Prismatic	Resources, machining cost
Bo <i>et al.</i> [2006]	Prismatic	Precedence relations, optimality	
P S O	Mohemmed <i>et al.</i> [2008]	Both rotational and prismatic	Shortest route
	Guo <i>et al.</i> [2009]	Prismatic	TAD, manufacturing resources, cost
	Guo <i>et al.</i> [2009]	Prismatic	TAD, manufacturing resources, time
A C O	Vijaykumar <i>et al.</i> [2003]	Rotational	Process parameters, cost
	Lv and Zhu [2005]	Prismatic	Workshop resources, time and cost
	Krishna and Rao [2006]	Prismatic	Precedence relations, tolerance

### 2.3.4 Fuzzy Logic based Approaches

Fuzzy logic is used to deal with reasoning under uncertainty. Fuzzy logic derives its motivation from approximate reasoning. The application of fuzzy logic offers the advantage of structured knowledge representation (similar to that of expert systems) in the form of rules with linguistic labels. Moreover, it is able to handle uncertainty and reason with imprecise information. It can be used in human decision making process to draw conclusions from vague, ambiguous information. With fuzzy logic, the precise value of a variable is replaced by a linguistic description, which is represented by a fuzzy set, and inference is drawn based on this representation. The benefit of using fuzzy logic is the ability to solve practical, real world problems, which invariably involve some degree of imprecision and uncertainty. The procedural knowledge in fuzzy logic based systems is expressed as fuzzy IF–THEN rules. A background of fuzzy systems is presented in Section 4.2,

Chapter 4. Fuzzy logic have been used in CAPP for automating process planning, setup planning, selection of cutting parameters for machining, *etc.*

Setup planning and feature relations have been the focus of extensive research by Ong and Nee [1994, 1995, 1996, and 1997]. Precedence relation between two features may depend on many uncertain factors. This fact was realized by Ong and Nee as early as 1994. They represented the imprecise feature relations using fuzzy sets and fuzzy relations to generate setup plans for prismatic parts fulfilling the requirements of process planning and fixture planning. The authors applied the concept of feature dependency grades to deal with uncertain feature relations. Feature relations and their dependency grades generate the feature precedence relations for grouping features into setups. Different feature relations such as geometric relation, tolerance relation, datum and fixturing relations, and heuristic relations are considered. Setup planning knowledge is represented as production rules in these approaches. The same authors [1998] stressed that fixturability analysis of the different features of a part and the part as a whole is an inevitable part of setup planning, neglecting which may lead to infeasible setup plans. They proposed a fixturability evaluation method for a part in two levels using fuzzy logic. At the micro level, each feature is accessed for its suitability to be used as a fixturing element considering its surface area, surface finish, face-feature relationship, orientation, intricacy, symmetry, *etc.* At the global level, the overall fixturability of the part is accessed after setup plans are made for the part based on stability of the part and the cost estimation of the fixturing system. Even if the methodology is for prismatic parts, it is applicable to castings and non-prismatic parts too.

Zhang and Huang [1994] solved the process plan selection problem with a fuzzy set based approach by evaluating the process plans quantitatively based on maximum contribution to the shop floor. First, a set of process plans with maximum contribution to the shop floor is identified, and then a progressive refinement strategy is applied to the set to reduce the manufacturing resources needed. The objectives considered are minimum number of setups, machining steps, and machining time. Zhao [1995] presented a similar approach of optimal process plan selection using fuzzy sets and fuzzy decision making strategy. Initially, a set of alternative process plans are generated using alternative machining operations,

machine tools, and cutting tools. Fuzzy decision making strategy is applied to find the optimal process plan with the objectives of minimum machining time, minimum number of setups, and minimum dissimilarity among the machine tools and cutting tools.

Gu *et al.* [1997] emphasized on feature prioritization for simplifying operation sequencing in machining of prismatic parts. The authors presented a combined fuzzy logic and neural network model to evaluate feature priorities based on manufacturability of the features and identify the important features. Tool capability, symmetry, orientation, accessibility, intricacy, *etc.* are some of the parameters for evaluating manufacturability of features. Criteria used for operation sequencing are minimum number of setups and tool changes and non-violation of feature precedence relations.

Wu and Zhang [1998] proposed an object oriented approach for generating alternative setup plans and fuzzy set theory is applied to find the optimal setup plan for machining of prismatic parts. The authors are of the view that a rigid optimal setup plan may not be optimal in a changed manufacturing environment, so there should be alternative optimal plans to adapt to the dynamic manufacturing resources. Three types of classes are defined to represent the setup planning knowledge in object oriented approach, *viz.* process control class, setup generation class and setup evaluation class. A setup evaluation function is formulated to evaluate the generated setup plans using fuzzy set approach considering dimensional and geometric tolerances, precision of the part, satisfaction of the basic setup planning rules, *etc.* After evaluating a set of candidate setup plans, an optimal setup plan with the highest evaluation function value can be obtained.

Wong *et al.* [2003] used a hybrid of fuzzy expert system FuzzyCLIPS and GA for machining operation selection and operation sequencing under uncertainty for prismatic parts. Optimal operation sequence is found based on manufacturing resource and cost. First, a local optimal operation sequence is generated satisfying feature precedence relations and then a global optimal operation sequence is searched based on manufacturing resources and cost.

Gaoliang *et al.* [2005] used a hybrid of fuzzy set theory and Hopfield neural network for setup planning of prismatic parts. The setup planning problem is divided into setup formation, operation sequencing and setup sequencing sub-problems. The setups are formed based on the optimal TAD of the features. A fuzzy set based algorithm is used to find the optimal TAD of features. Using production rules and fuzzy set theory, the feature precedence relationships matrix (FPR) is formed considering feature geometry, tolerances, datum relationship, heuristic rules and manufacturing cost. Operation sequencing and setup sequencing is done based on the FRP. A similar setup planning approach is developed by Wenjian and Gaoliang [2005] which can be integrated with the Internet. Java and Web technologies coupled with XML (eXtensible Modeling Language) file format provide means for the transfer of information between various manufacturing systems. A fuzzy set theory based approach for setup planning is introduced considering TAD, tolerance requirements, precedence relations, manufacturing cost, and good manufacturing practice. Another Internet-based integrated setup planning and fixturing system can be found in Gaoliang *et al.* [2005]. The proposed system has client/server architecture comprising an information server, a database server, and a number of setup planning clients. The use of Java and XML (eXtensible Modeling Language) file format adds flexibility to the system and operable under different platforms. Yuru and Gaoliang [2005] developed an integrated setup planning and fixture design method using a hybrid of knowledge-based and fuzzy set based approach. Tolerance among the features, feature precedence relations, fixturing requirements, and manufacturing cost are the main constraints considered. Table 2.9 shows some fuzzy logic based setup planning efforts.

The main weaknesses of fuzzy logic based methods are that they are restricted to the fields where expert knowledge is available and are unable to automatically acquire knowledge. The problem of finding appropriate membership functions for the fuzzy variables also poses a challenge to the researchers.

**Table 2.9.** Major Setup planning approaches using fuzzy logic

F U Z Z Y  L O G I C  B A S E D  A P P R O A C H E S	References	Type of part	Main constraints considered
	Ong and Nee [1994, 1995, 1996, and 1997]	Prismatic	Precedence relations due to feature dependency, tolerance, fixtures,
	Zhang and Huang [1994]	Prismatic	Resources, uncertainty, machining time
	Zhao [1995]	Prismatic	Resources, uncertainty
	Gu <i>et al.</i> [1997]	Prismatic	Feature prioritization, part geometry, TAD
	Ong and Nee [1998]	Prismatic	Fixturability, precedence relations, tolerance
	Wu and Zhang [1998]	Prismatic	Precedence relations, TAD, tolerance
	Wong <i>et al.</i> [2003]	Prismatic	Precedence relations, uncertainty, resources
	Gaoliang <i>et al.</i> [2005]	Prismatic	Precedence relations, TAD, tolerance
	Wenjian and Gaoliang [2005]	Prismatic	Precedence relations, TAD, tolerance, cost
	Gaoliang <i>et al.</i> [2005]	Prismatic	Precedence relations, TAD, tolerance
	Yuru and Gaoliang [2005]	Prismatic	Precedence relations, tolerance, cost, fixturing
	Amaitik and Kilic [2007]	Prismatic	TAD, tolerance, surface finish, part geometry

## 2.4 Summary of Literature Review and Challenging Issues

From the review of literature on setup planning, some critical observations are made and challenging issues are identified. Following is the summary of major observations found from the literatures:

- It is observed that although there is success in automating some portions of process planning, *viz.* operation sequencing, cutter path optimization, fixture design, *etc.*, there is not yet an automatic setup planning system fulfilling the requirements of commercial application. Absence of a standard definition of optimality of setup plans may be the reason behind this. Different researchers have used different objectives for finding optimal setup plans. A universally accepted definition of optimal setup plan, its evaluation criteria, a common scale for comparing optimality of different setup plans are absent in the literature.
- Part geometry, tool approach direction of a feature, feature interactions, tolerance requirements, feature precedence relations, manufacturing resources, and fixturing and datum/reference requirement are the major manufacturing constraints to be considered in setup planning. Researchers have carried out setup planning considering all or combinations of some of these constraints. For

optimizing setup plans, the most commonly used objectives are the minimum number of setups/minimum setup time /minimum setup cost.

- For setup planning problems, use of AI techniques is gradually increasing, giving better results compared to traditional methods of setup planning. Some of the important soft computing techniques used by researchers are artificial neural networks, fuzzy logic, expert systems, evolutionary algorithms such as genetic algorithm, simulated annealing, ant colony optimization, particle swarm optimization, *etc.* Expert systems are good at logic, neural network is good for acquiring knowledge from examples, evolutionary algorithms are advantageous for optimization, and fuzzy logic is best used for dealing with reasoning under uncertainty.
- Study of literature reveals that various techniques have been used for setup planning giving prime importance to tolerance achievement, fixturing requirements, optimization of setup plans, *etc.* Tolerance driven approaches ensures good quality of the part, but only tolerance consideration alone can not generate optimal setup plans unless other constraints are also considered. Fixture driven approaches, with proper integration of setup planning and fixturing can give practical solutions. Constrained optimization approach may be a promising venture for future research to find a truly global optimal setup plan considering all possible solution space.
- It is observed from the literature review that importance is shifted from stand-alone setup planning system to dynamic setup planning system in geographically distributed manufacturing environment. In the emerging trend of agile and virtual manufacturing, a part is designed and manufactured in different sites using the facilities available in a multi-enterprise scenario. Java and Web technologies provide means for the transfer of information between various manufacturing systems.

Some challenging issues that can give new direction to setup planning research are enumerated as follows:

- For setup planning problems, conventional mathematical/logical algorithms are not readily available and applications of those do not yield satisfactory solutions. Setup planning incorporates expert knowledge in various stages collecting it

from different sources. However, there may be uncertainty in the collected knowledge which affects the final outcome of the setup plan. Decision making in setup planning involves the use of uncertain knowledge to a large extent. The performance of a setup planning system depends to a large extent on the way uncertainty is managed by the system. However, this aspect is not given its due importance in setup planning approaches found in the literature. It is observed that the efforts dealing with the uncertainty in the knowledge-base are limited.

- Adaptability of the setup plans to changing manufacturing environment is an important issue. Traditional software systems for automating setup planning are static in nature and they do not respond to the changes in the situation. There is a need to develop an adaptive and dynamic setup planning system for lean and agile manufacturing.
- Fuzzy set theory is used in several efforts of setup planning as found from the literature review. For a fuzzy input or output variable, membership grades are assigned to map numeric data to linguistic fuzzy terms. Design of fuzzy membership functions/membership grades greatly affects a fuzzy set based inference system. The problem of finding appropriate membership functions/membership grades for the fuzzy variables poses a challenge to the researchers.
- Although a number of attempts are found in the literature for an integrated setup planning system, they do not provide sufficient information to the other phases of process planning. The output of the traditional setup planning approaches is limited and insufficient for the upstream process planning activity, such as fixture design. There is a need to develop a robust and practical setup planning solution considering setup, fixturing and machining constraints simultaneously.

## 2.5 Scope and Objectives of the Present Work

Based on the literature survey and major challenges identified in the last section, it is decided to explore the following aspects of setup planning in this thesis:

- 1. Exploring the application of expert system and fuzzy sets for setup planning and uncertainty management:** It is difficult to solve setup planning problems using traditional deterministic algorithms. Moreover, setup planning has to be carried out in an environment of uncertainty. Solution methods should be built on an intelligent architecture with the composite use of AI techniques. Expert system and fuzzy set theory are two important AI techniques. Expert systems are good at logic and fuzzy sets are best used for reasoning under uncertainty. One important aspect observed from the literature review on setup planning is that most of the research efforts considering uncertainty dealt with the uncertainty on the shop floor, *viz.* resource and capacity constraints, machine breakdown, and tool failure, but not the uncertainty in the knowledge-base. Exploring the benefits of using expert system for setup planning and fuzzy sets to deal with the uncertainties associated with setup planning knowledge is the major objective of the thesis. A fuzzy set based approach is proposed to manage uncertainty in the knowledge-base with fuzzy membership grades. It deals with the uncertainty among the feature precedence relations as well as the uncertainty in datum selection for each setup.
- 2. A methodology for updating the knowledge-base of the setup planning system:** Adaptability of the setup plans to changing manufacturing environment is an important issue. Capability of learning from feedback and adapting to the actual condition on the shop floor is essential for setup planning systems. One of the objectives of the present thesis is to develop a strategy for adaptive learning from the feedback received from actual production stage and modify and adapt the knowledge-base to the actual situations on the shop floor. Thus, the setup planning system will keep evolving with experience.
- 3. A methodology for fine tuning the fuzzy membership grades:** For a fuzzy input or output variable, membership grades are assigned to map numeric data to linguistic fuzzy terms. Design of fuzzy membership functions/membership grades greatly affects a fuzzy set based inference system. The knowledge of human experts plays a vital role in assigning these membership grades. Most

of the time, different estimates of a fuzzy variable are decided based on expert's opinion. However, there is a need to optimize these estimates to enhance performance. In view of it, another objective of the present thesis is to develop a strategy for fine tuning the initial membership grades assigned by experts for finding optimal membership grades. It is proposed to conduct a series of experiments and then combine the best of an expert's knowledge and experimental data to predict the membership grades of fuzzy parameters.

4. **An experimental study on the effect of datum surface roughness on tolerances:** Surface roughness of the datum face is an important criterion to be considered for the selection of the datum during setup planning as it can affect the tolerances among the features. However, in the literature, not much work is available that relates the effect of datum surface roughness to the geometrical tolerances of a component. One of the objectives of the present thesis is to experimentally investigate the effect of datum surface roughness on two geometric tolerances, *viz.* parallelism and perpendicularity in machining of prismatic components.
5. **Incorporation of fixturing requirements in setup planning:** It is observed from the literature review that the output of the traditional setup planning approaches is limited and insufficient for the upstream process planning activity, such as fixture design. One of the objectives of the present thesis is to develop a setup planning system considering fixturing aspects for machining of prismatic parts that also provides the following output: recommended depth of cut/feed in fuzzy form, machining and clamping forces in fuzzy form, approximate optimal locator and clamp layout and sizes of the locators and clamps. Moreover, the uncertainties associated with the work material, clamp material and clamping torque are considered by means of fuzzy arithmetic.

## Framework of Setup Planning Expert System

### 3.1 Introduction

The basic framework of the setup planning expert system is described in detail in the present chapter. It has been implemented on a PC using the expert system shell CLIPS, an acronym for C Language Integrated Production System [Giarratano and Riley, 1998]. Given the information about different features present in a part, machining operations, machine tools, cutting tools and material properties as input, the setup planning system automatically performs the tasks of setup formation, operation sequencing, datum selection for each setup and generation of information related to fixturing. It is capable of generating setup plans for machining prismatic parts containing different types of features, *e.g.* face, hole, slot, pocket, step, chamfer and so on including interacting features. Two volumetric features are defined as interacting features if their boundaries intersect, so that they share a non-empty, common volume [Gao and Shah, 1998]. In this chapter, a background on expert systems is presented in Section 3.2 followed by an introduction to expert system shell CLIPS in Section 3.3. The different modules of the setup planning expert system are presented in Section 3.4. Finally, a summary is presented in Section 3.5.

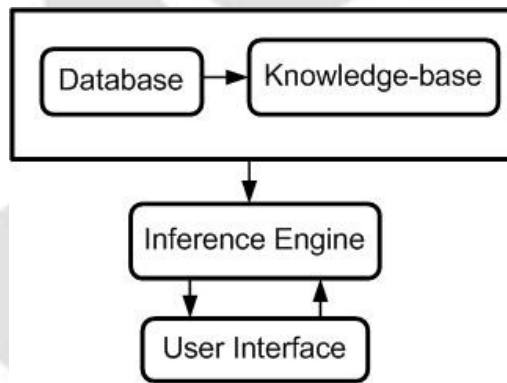
### 3.2 A Background of Expert Systems

An expert system is an artificial intelligence (AI) tool used to solve problems that normally require human intelligence. It is a computer program that contains subject specific knowledge of one or more experts. Expert's knowledge in a specific field is collected and stored in the knowledge-base of the expert system. One of the important needs for expert system development is to capture human expertise and use it. Human expertise is scarce and is lost due to retirement, transfer, *etc.* An expert system analyzes the user supplied information about a specific problem and

utilizes reasoning capabilities to draw conclusions. It emulates the problem solving and decision making capacities of a human expert. The different components of an expert system are:

- Knowledge-base containing domain specific knowledge collected from experts, books and manuals.
- Database containing declarative knowledge (facts) about the problem.
- Inference engine which is the reasoning mechanism that provides conclusions.
- User interface by which the user communicates with other components of the expert system.

Figure 3.1 shows the basic components of an expert system.



**Figure 3.1.** Components of an expert system

Knowledge-base in an expert system contains the domain specific knowledge that is used to solve problems. The knowledge is elicited by the knowledge engineer/system developer from various experts, books and manuals. The collected knowledge can be represented and stored in the knowledge-base in various forms. One of the most commonly used forms of knowledge representation is IF-THEN rules. Expert systems whose knowledge is represented in rule form are called rule-based expert systems. Other methods of representing knowledge are semantic networks, conceptual graphs, frames, object oriented schemes and Petri nets [Nikolopoulos, 1997]. The rules are represented in natural language (*e.g.* English). Therefore the knowledge-base can be developed rapidly without the need to perform

extensive programming. Adding, modifying, or deleting rules does not require extensive system changes. An IF–THEN rule can be represented in the form:  $A \rightarrow B$ . This is interpreted as ‘IF condition A is satisfied THEN action B occurs’. The A portion is called the antecedent part and the B portion is called the consequent part of a rule.

The database contains a set of facts about the problem to be solved which is used to match against the IF parts of rules stored in the knowledge-base. For example, the facts necessary for a machining problem may include part geometry, machining operations, dimensions and tolerances of the part, and machine tool and cutting tool information. The information needs to be converted from its original data format to the representation format for facts supported by the expert system.

The inference engine contains and realizes the decision making strategy. It is an independent module that makes the expert system more flexible. The inference engine links the rules in the knowledge-base and the facts in the database to form a line of reasoning for drawing inference. There are two methods of reasoning by which the inference engine arrives at some decision, forward chaining and backward chaining. Forward chaining supports data-driven reasoning. In this method, the inference engine starts from a set of conditions and moves towards a conclusion. It tries to match the available facts from the database with the antecedent part of the rules in the knowledge-base. When matching rules are found, the consequent parts of the rules are executed. Thus new facts are generated which in turn cause other rules to fire. This process continues until no more matching rules are available. GARI, AGFPO, SIPPS, DOPS and FEXCAPP are some process planning systems that use forward chaining reasoning strategy [Kiritsis, 1995]. Backward chaining supports goal-driven reasoning. The conclusion/goal is known and the inference engine checks the consequent parts of the rules in the knowledge-base to find a matching for the goal. If matching is found, facts are searched to cause any of those rules to fire. TOM, CUTTECH, EXCAP process planning systems use backward chaining reasoning strategy [Kiritsis, 1995]. The user interface is the means of communication between a user and the expert system. Input to the expert system, output of the final results and decisions are communicated through this interface.

The methods for developing expert systems can be classified into two types, *viz.*, programming from scratch and using expert system shells. The use of programming provides more flexibility and control to the developer. Artificial intelligence languages such as LISP (List Processing), PROLOG (Programming in Logic) and conventional programming languages such as C, Pascal, Java, *etc.* can be used for developing expert systems. However, developing a complete expert system using programming requires greater expertise and tremendous amount of time and work. To simplify the task of expert system development, expert system shells are used. An expert system shell is a software system where the developer has to build the knowledge-base. It contains a built-in inference engine, a user interface, a set of knowledge representation structures and facilities to interface with external systems. Some examples of expert system shells are EMMYCIN (Empty MYCIN), EXSYS (Expert System Shell), CLIPS (C Language Integrated Production System), ART (Automated Reasoning Tool), G2, LEVEL5, *etc* [Nikolopoulos, 1997]. Using expert system shells can speed up the expert systems development time. In the present work, CLIPS expert system shell is used for developing the setup planning expert system. A brief description of CLIPS is presented in the following section.

### **3.3 CLIPS: An Expert System Shell**

CLIPS is an expert system shell, an acronym for C Language Integrated Production System [Giarratano and Riley, 1998]. CLIPS was first developed in 1986 by the software technology branch, NASA, Johnson Space Centre and has been undergoing continuous refinement and improvement since then. It is designed to facilitate the development of software to model human knowledge and expertise. CLIPS provides support for rule-based, object-oriented, and procedural programming. Some important features of CLIPS are flexibility, easy integration with external systems and availability. CLIPS is now maintained independently from NASA as a public domain software. CLIPS is called an expert system tool because it provides a complete environment for developing expert systems which includes features such as an integrated editor and a debugging tool. A program

written in CLIPS consists of rules and facts. The basic features of rule-based programming capabilities of CLIPS are discussed hereunder.

A set of knowledge representation structures (called Construct) are provided in CLIPS to facilitate insertion of facts and rules into the expert system. Some examples of CLIPS Construct are Deftemplates, Deffacts and Defrules. In order to solve a problem, a CLIPS program must have data or information about the problem which it can reason with. A piece of information is called a fact in CLIPS. Before facts can be entered, CLIPS must be informed of the list of valid fields/attributes associated with each fact. The construct Deftemplate is used to define the format for representation of facts. It is a list of named fields called slots used to store various attributes. For example, the facts about a machining feature may be entered in the format of a Deftemplate consisting of several slots as follows:

```
(Deftemplate: machining_feature
(slot number (type INTEGER))(slot name(type SYMBOL))
(slot type(type SYMBOL)) (slot subtype(type SYMBOL)))
```

According to the above Deftemplate, a machining feature can have the slots/attributes such as feature number, feature name, feature type and subtype. Following the above format, the facts about a group of machining features can be entered using the Deffacts construct as follows:

```
(Deffacts: machining_feature_list
(feature (number 1) (name FACE) (type EXTERNAL) (subtype PRIMARY))
(feature (number 2) (name HOLE) (type INTERNAL) (subtype SECONDARY))
(feature (number 3) (name STEP) (type EXTERNAL) (subtype SECONDARY)))
```

The Defrule construct is used to build the rule-base of the expert system. For example there is a rule:

```
IF a hole is to be drilled on a chamfered face
THEN drill the hole first and then chamfer.
```

Using Defrule construct, the rule is inserted to the rule-base as follows:

```
(Defrule::feature_precedence_constraint
(feature(number ?a)(name HOLE)(type INTERNAL)(subtype SECONDARY)
(adjacent_features ?b)(adjacent_feature_names CHAMFER))
=> (assert(feature_precedence ?a ?b)))
```

Besides dealing with symbolic facts, CLIPS also can perform numeric calculations. Functions have been included in CLIPS for performing various calculations. The inference engine of CLIPS is based on the forward chaining strategy. It attempts to match the patterns (antecedent part) of rules against facts in the fact-list. If all the conditions in the antecedent part of a rule match facts, the rule is activated and put on the agenda. The agenda is a collection of activations of those rules which have found matching facts. When multiple activations are on the agenda, CLIPS automatically orders the activations on the agenda in terms of increasing priority. The priority order for firing of rules can be implemented by using a unique feature of CLIPS called 'salience'. It is a mechanism to assign priorities (in terms of numeric values) to rules when multiple rules are present. A rule with higher salience fires before a rule with lower salience. The inference engine sorts the activations according to their salience. This sorting process is called conflict resolution.

All the rules and the facts about the problem to be solved are to be encoded following the syntax of CLIPS and saved as files with the extension .clp. The program is executed using the CLIPS expert system shell version 6.3 compiler under the Windows environment. At the time of execution of the expert system program, the following steps are to be performed.

- Load the program files from the knowledge-base into the CLIPS environment using the option 'Load CLIPS Construct' from File menu.
- Load input data from database into the CLIPS environment using the option 'Load CLIPS Construct' from File menu.
- Execution of the program is performed by first selecting 'Reset' and then 'Run' options from the Execution menu.

### 3.4 Development of the Setup Planning Expert System

The overall architecture of the proposed setup planning expert system is shown in Figure 3.2. Its modules are the database, the rule-based knowledge-base, a fixturing information generation module, uncertainty and feedback module, the inference engine and the user interface. It has been implemented on a PC using the expert system shell CLIPS described in the previous Section. The detail of each module of the proposed system are discussed hereunder.

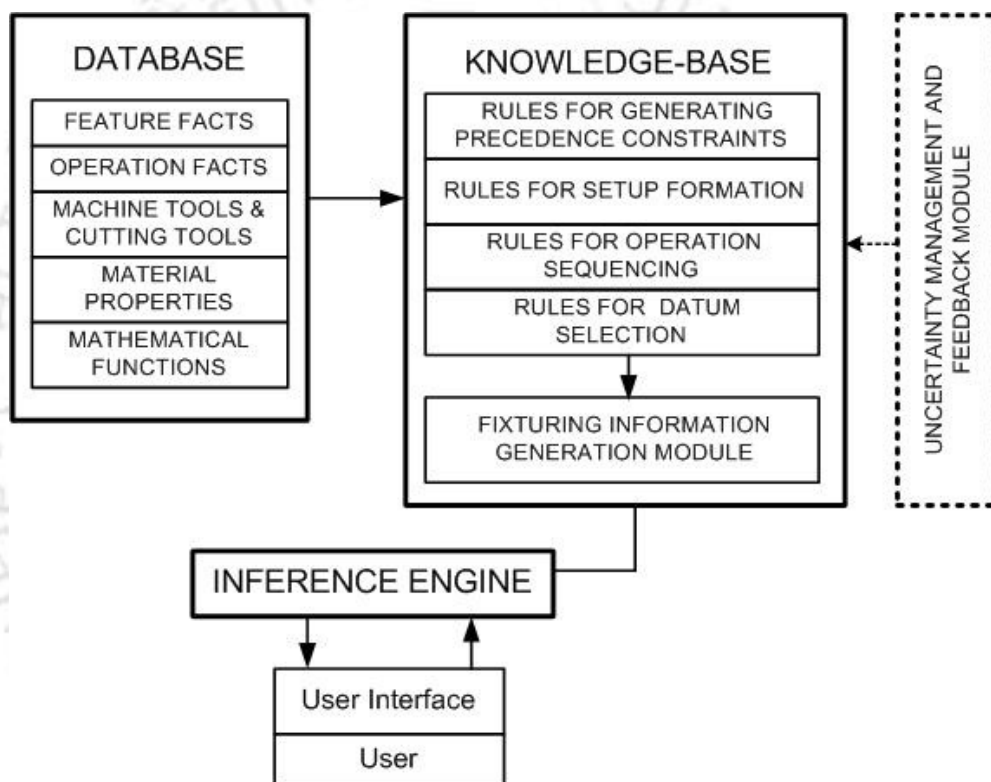


Figure 3.2. Architecture of the setup planning expert system

#### 3.4.1 Database

The database contains the declarative knowledge that includes the detailed information about the different features present in the part and the machining operations required to produce them. This information is presented in the form of data files and given by the user as input to the expert system. Information about machine tools, cutting tools and material properties are also to be included in the database. The database also contains mathematical functions and external programs

that are necessary for performing different calculations. The following section explains the format of representation of the input data to the expert system.

#### 3.4.1.1 Machining Feature Information

The input information on machining features includes the type of features present in a part, their dimensions, the geometric tolerance relationship with other features, the tool access directions (TAD), feature identifier number, *etc.* Each of these attributes of a feature is called a 'slot'. The concept of Deftemplate (a CLIPS Construct) has been used to define the format for representation of the above input data to the expert system. Deftemplate is a list of named fields called slots used to store various above mentioned feature attributes. A slot may contain one or more fields. Each slot of a feature stores values, a single value in case of a single slot and multiple values in case of a multislot. For example, a feature can have only one name, so the attribute 'name' has single slot and has only one value. However, a feature may have more than one TAD. Therefore, TAD is a multislot attribute with multiple values for TAD. The input data for a feature may be entered in the format of a Deftemplate consisting of several slots as follows:

*(Deftemplate: feature*

*(slot number (type INTEGER))(slot name(type SYMBOL))*

*(slot type(type SYMBOL)) (slot subtype(type SYMBOL))*

*(slot length(type NUMBER)) (slot breadth(type NUMBER))*

*(multislot TAD (type SYMBOL))*

*(multislot ref-features(type INTEGER))*

*(multislot adjacent\_features(type INTEGER))*

*(multislot relation\_with\_feature (type INTEGER))*

*(multislot tolerance (type NUMBER))*

It has one slot each for the feature identifier number, name of the feature, type and sub-type of feature, feature length, breadth, TAD of feature, identifiers of the reference features, adjacent features and features with which it has tolerance

relations, respective tolerances, *etc.* Using the above Deftemplate, the input data for a typical feature may be entered as follows:

*(feature (number 10) (name FACE)(type EXTERNAL) (subtype PRIMARY)  
(length 12.5)(breadth 8) (TAD TAD4 TAD6)(ref-features 14 16)  
(adjacent\_features 7 9 12)(relation-with-feature 12 15) (tolerance 0.2 0.1)).*

It states the fact that there is an external primary feature face with feature identifier number 10, having two TADs– TAD4 and TAD6, of length and breadth 12.5 cm and 8 cm respectively which is referenced with respect to features 14 and 16. The face has features 7, 9 and 12 as adjacent features. It has tolerance relations of value 0.2 mm and 0.1 mm with features 12 and 15 respectively.

#### 3.4.1.2 Machining Operation Information

The information on machining operations includes operation identifier, operation type, and the feature on which it acts, its TAD and tolerance relationships with other features. Another Deftemplate has been used to define the format for representation of the input data about machining operations as follows:

*(Deftemplate: operation  
(slot number (type INTEGER)) (slot type (type SYMBOL))  
(slot on-feature (type INTEGER)) (multislot TAD (type SYMBOL))  
(multislot relation-with-feature (type INTEGER))  
(multislot tolerance (type NUMBER))*

The input data for a machining operation may be entered in the above Deftemplate format as follows:

*(operation (number 100) (type mill) (on-feature 5) (TAD TAD3 TAD5)  
(relation-with-feature 7 12) (tolerance 0.1 0.2)).*

It states that milling operation with the identifier number 100 is to be performed on feature 5. The operation has two TADs– TAD3 and TAD5 and tolerance relations

of value 0.1 mm and 0.2 mm with features 7 and 12 respectively. There are two ways by which the above input data on features and machining operations can be entered into the developed expert system. It can be saved as data files with the extension .clp and loaded from the file into the expert system environment at the time of execution. Alternatively, it may be also directly entered manually by typing through a user interface.

#### *3.4.1.3 Mathematical Functions and Other Required Information*

In addition to feature and machining operation information, database contains different mathematical functions to perform mathematical calculations, *e.g.* functions to compare the tightest tolerance relations, functions to determine the largest area face. Moreover, information on machine tools and cutting tools to machine the features present in a part, material properties of the workpiece material, locating and clamping element materials are to be given as input to the expert system through the database.

### **3.4.2 Knowledge-base**

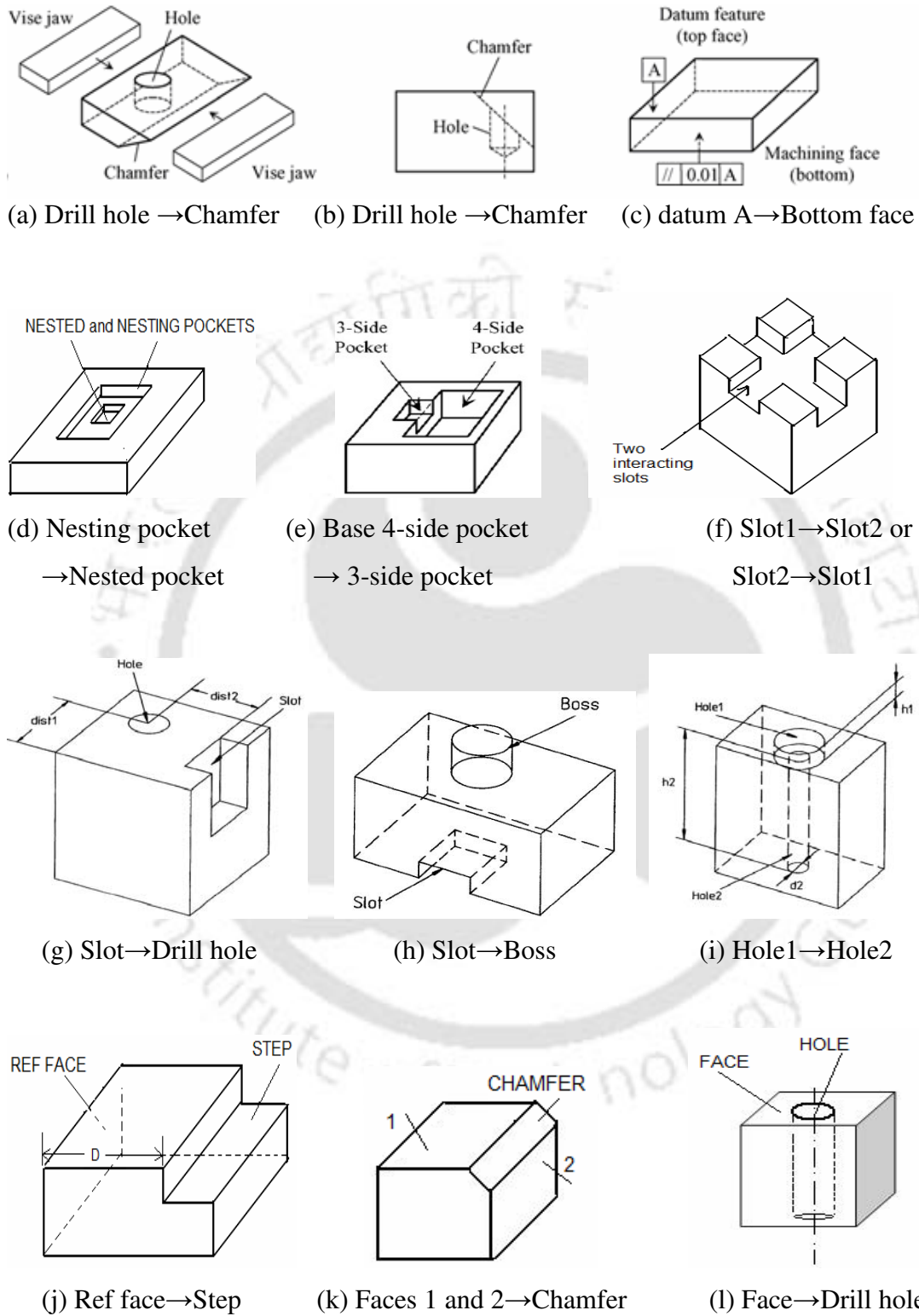
The knowledge-base contains the problem solving knowledge of the expert system. Setup planning knowledge is incorporated in the form of IF–THEN rules in the knowledge-base. The necessary knowledge for formulating the rules is based on heuristic and expert knowledge from various sources such as handbooks, textbooks and interviews with experts and skilled machinists. Some knowledge is gathered from observations of actual machining in the shop floor. Four sets of rules have been developed for generation of machining precedence constraints, setup formation, machining operation sequencing within each setup and selection of datum for each setup. The methodology for generating these rules is discussed in the following sub-sections.

#### *3.4.2.1 Generation of Machining Precedence Constraints*

During machining of the features comprising a part, certain precedence relations among the features are to be respected. These precedence relations arise due to basic manufacturing principles and feature interactions. A precedence relation between

two features F1 and F2, denoted as  $F1 \rightarrow F2$ , implies that F2 cannot be machined until the machining of F1 is complete. Different precedence relations are obtained due to area/volume feature interactions, tolerance relations, feature accessibility, tool interaction, fixturing interaction, datum/reference/locating requirements, and constraint of good manufacturing practice. Figure 3.3 shows some of the precedence relations collected from the literature.

Figure 3.3. (a) depicts a precedence constraint arising due to fixturing interaction. Drilling the hole should precede the chamfer as fixturing will be difficult for drilling after chamfering. There will be less contact area for clamping the vise jaw if chamfering is done first. For similar reason, the slot precedes the boss in Figure 3.3. (h). An accessibility/tool interaction constraint is shown in Figure 3.3. (b) where positioning the drilling tool will be difficult if chamfering is done first. Figure 3.3. (c) depicts the precedence constraint arising due to tolerance relation with the datum feature. The bottom face has tolerance relation with the datum face A and face A is to be machined first. Figure 3.3. (d) shows two nested pockets having volumetric interaction, *i.e.* common volume to be removed. The smaller pocket is nested in the bigger pocket and the machining of the bigger/nesting pocket precedes the smaller/nested pocket. This type of precedence relation is called parent-child relation. The parent/nesting feature is to be machined prior to the child/nested feature. In Figure 3.3. (e), the two pockets have only area interaction in the form of a common face. The 4-side base pocket is opening up to another 3-side pocket and the convention is to machine the base feature first. Figure 3.3. (f) is a case of no precedence; any of the two slots can be machined first. Figures 3.3. (g) and (j) show the precedence of machining the reference features first. In (g), the hole is referenced with respect to the slot and in (j), the step is referenced with respect to the vertical face and reference features are to be machined first. Figure 3.3. (i) shows good manufacturing practice of drilling the smaller depth hole prior to higher depth hole. Figures 3.3. (k) and (l) show the precedence of machining the adjacent faces first and then chamfering/drilling.



**Figure 3.3.** Different precedence relations collected from the literature

Figs.(a)–(e) presented with permission from Liu and Wang, Copyright[2007] Elsevier, part of Fig.(f) from Pal *et al.*, Copyright[2005] Elsevier, Figs.(g)–(i) from Zhang *et al.*, Copyright[1995] Elsevier

These feature precedence relations are derived from manufacturing practice and there may be uncertainty about the validity of some assumed relations. The optimal machining sequence depends to a large extent on precedence relations. The validity of the precedence relations are to be reviewed keeping in mind the other related factors such as machining cost and time, work material properties, the required surface finish, machining passes (single or multi), *etc.* In Chapter 4, detail of an approach to deal with uncertainty in the precedence relations are discussed.

In the proposed approach for setup planning, a set of rules have been developed to automatically identify the various precedence relations between the features and the machining operations needed to produce them. The following are the examples of some rules that have been included as a part of the knowledge-base for determining the precedence relations. A total of 16 rules have been developed for generating precedence relations.

A sample rule for generating tool interaction constraint may be written using the Defrule construct in CLIPS as follows:

```
(Defrule ::precedence_constraint "precedence based on drilling a hole prior to the
chamfer"
(feature(number ?a)(name HOLE)
(type INTERNAL)(subtype SECONDARY) (secondary_to ?b)
(adjacent_features ?b) (adjacent_features_names CHAMFER))
=>(assert(feature_precedence ?a ?b)))
```

The above rule states that if there is a feature *a* of name hole which is to be drilled on a chamfered face *b*, then due to tool interaction constraint, the drilling of hole *a* is to be done prior to the chamfer *b*. Another rule for generating parent-child precedence constraint is given below. It states that if there is an internal feature *a* which is nested in another feature *b*, then due to parent-child precedence constraint, the machining of feature *b* is to be done prior to the machining of *a*.

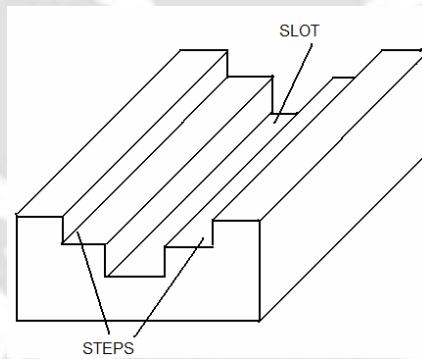
*(Defrule::precedence\_constraint "precedence based on machining of nesting features prior to the nested features"*

```
(feature (number ?a)(type INTERNAL)(subtype NESTED )(nested_in ?b))  
=>(assert(feature_precedence ?b ?a)))
```

A precedence rule for machining the two steps and an intermediate slot as shown in Figure 3.4. is given hereunder. It states that if there is an external slot which is a secondary feature to the two steps as shown in Figure 3.4., machining of the steps are to be done prior to the slot between them.

*(Defrule::precedence\_constraint "precedence based on machining of adjacent external steps prior to that of the slot between them"*

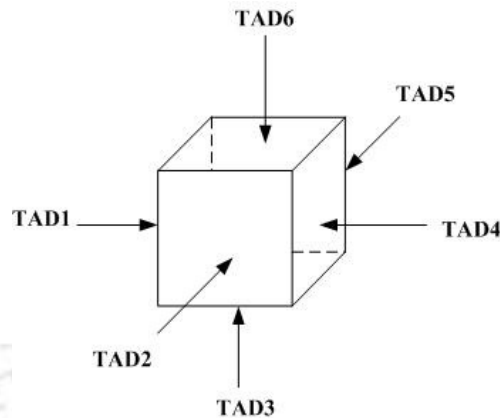
```
(feature (number ?a)(name SLOT)(type EXTERNAL)(subtype SECONDARY)  
(adjacent_features ?b ?c)(adjacent_features_names STEP STEP))  
=>(assert(feature_precedence ?b ?a))  
    (assert(feature_precedence ?c ?a)))
```



**Figure 3.4.** Two steps and a slot

#### 3.4.2.2 Setup Formation

Setups are formed by clustering the features and their machining operations into different groups based on TAD and tolerance relations among features. A prismatic part can have six TADs as shown in Figure 3.5.



**Figure 3.5.** Six tool approach directions for a prismatic part

The following methodology is adopted for grouping of features for setup formation:

- Features with a common single TAD are grouped together to form a common TAD feature cluster. A common TAD feature cluster can be machined in the same setup.
- The features having multiple TADs are assigned a single TAD based on their tolerance relations with other features. For example, if a multiple TAD feature (say *a*) has tolerance relation with only one feature (say *b*) having a single TAD, then the feature *a* is assigned the TAD of *b*.
- If a multiple TAD feature (say *a*) has tolerance relation with more than one feature (say *b* and *c*) each having a single TAD, then the feature *a* is assigned the TAD of *b* or *c*, depending on whichever has tighter tolerance relationship with *a*.
- If a multiple TAD feature has no tolerance relationship with other features, it is assigned the TAD of a feature cluster where there are the maximum numbers of features. Machining of the maximum number of features in the same setup with the same datum will ensure better tolerance achievement and reduced machining time and cost.

After grouping of features based on TAD and tolerance relations, setups are formed. For setup formation, different common TAD feature clusters are grouped together considering the machine capability in respect of feature access direction for machining. Various milling as well as drilling operations can be performed in a modern machining center (MC) equipped with rotary index table and automatic tool

changer (ATC). It is possible to machine five faces of a cubic workpiece in these machines in a single setup. Most of the machining centers contain simultaneously controlled three Cartesian axes X, Y, and Z. A set of rules and mathematical functions are used to implement feature clustering and setup formation as explained above. An example rule for feature clustering based on tightest tolerance is as follows (Feature *a* and feature *b* are taken as examples for explaining the rules in the rule-base):

```
(Defrule::feature_clustering_based_on_TAD_and_tolerance
?f1<-(operation(TAD $? TAD1 $?)(on_feature ?on_feature))
?f2<-(feature(number ?on_feature))
(test(>=(length$ (fact-slot-value ?f1 tolerance))2))
(operation(TAD TAD1)(on_feature =(feature-with-tightest-tolerance ?f1)))
=>
(modify ?f1(TAD TAD1(relation_with_feature =(update-relation-with-feature ?f1))
(tolerance =(update-tolerance ?f1)(modify ?f2(TAD TAD1)))
```

The above rule performs the following tasks:

- It identifies that there is a machining operation (fact identifier *?f1*) on feature *a* (fact identifier *?f2*) having multiple TAD and one of them is TAD1. It has tolerance relationship with more than one feature including (say) feature *b*. TAD of feature *b* is TAD1.
- Next, the mathematical function *feature-with-tightest-tolerance* compares the tolerance relations of machining operation on *a* and returns the fact identifier of feature *b* with which feature *a* has tightest tolerance. Operation on *a* is assigned the TAD of feature *b* i.e., TAD1.
- Lastly, the functions *update-relation-with-feature* and *update-tolerance* are used to update the slots *relation-with-feature* and *tolerance* respectively by removing the tolerance relationships between features that have been already considered.

If a multiple TAD feature has no tolerance relationship with other features, it is assigned the TAD of a feature cluster where there are the maximum numbers of

features. A sample rule for assigning a single TAD to a feature having multiple TADs and no tolerance relation with other features is explained hereunder. The machining operation (fact identifier *?f1*) for machining a slot (fact identifier *?f2*) has three TADs– TAD1, TAD2 and TAD3 and the slot does not have any tolerance relation with other features. Now, the machining operation and the feature slot are assigned a single TAD– TAD2 as there are maximum numbers of features in TAD2 feature cluster.

```
(Defrule::slot_with_multiple_TAD_no_tolerance_relation
?f1 <-(operation(TAD ?TAD1 ?TAD2 ?TAD3)(type mill)( on_feature ?on_feature))
?f2 <-(feature(number ?on_feature)(name SLOT))
=> (modify ?f1(TAD ?TAD2))
      (modify ?f2(TAD ?TAD2))
```

After forming all the feature clusters based on TAD and tolerance, setups are to be formed. Machining is performed in a vertical machining center (MC) equipped with rotary index table and automatic tool changer (ATC). It is possible to machine five faces of a cubic workpiece in these machines in a single setup. Therefore, machining of a part can be completed in two setups. The five common TAD feature clusters (TAD1, TAD2, TAD4, TAD5 and TAD6) are grouped into one setup and the remaining common TAD feature cluster TAD3 is assigned to the other setup. Sample rules for formation of setups based on TAD feature cluster is shown hereunder.

```
(Defrule::formation_of_setup-1
?f1 <-( TAD1 _feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-1*(fact-slot-value ?f1 operation_numbers))
      (bind ?*setup-1* (delete-member$(create$ ?*setup-1_feature_cluster*?
?*setup-1*)0)))
```

The above rule states that if there is a TAD1\_feature\_cluster (fact identifier *?f1*) with multiple operations all with TAD1, the operations are included in the setup-1 in their proper sequence. Initially, setup-1 had no element, which is now updated to

contain the operation numbers of TAD1 cluster. A similar rule for formation of setup-2 is shown below.

```
(Defrule::formation_of_setup-2
?f1 <-(TAD3_feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-2*(fact-slot-value ?f1 operation_numbers))
      (bind ?*setup-2* (delete-member$(create$ ?*setup-2_feature_cluster* ?
*setup-2*)0)))
```

A total of 42 rules have been developed for clustering of features and setup formation.

#### 3.4.2.3 Machining Operation Sequencing Within a Setup

Once the setups are formed, the machining operations within a setup are to be sequenced in a proper and feasible manner. Sequencing of machining operations within a setup is based on the machining precedence constraints generated earlier as described in Section 3.4.2.1. Moreover, one important criterion for machining operation sequencing is to minimize tool changes. By grouping the similar machining operations together, (for example, grouping all the drilling operations together) it is possible to reduce the number of tool changes and idle tool motion. Grouping of similar machining operations can be performed by using a unique feature of CLIPS called 'salience'. It is a mechanism for assigning priority to various rules. Thus when multiple rules are present, this feature allows a rule with higher salience to fire before a rule with lower salience. First, a sequence of operations is created within a setup based on their precedence relations. This operation sequence can be modified by grouping operations of same tool together as long as the precedence relations are respected.

For machining operation sequencing within a setup, the information on preceding operation for each machining operation is required. For example, the preceding operation for machining a nested feature is machining of the nesting feature which is again preceded by machining of its reference feature. These information/facts are created by the rules for generation of precedence relations. An

operation may have multiple preceding operations. First, a set of rules has been developed to find preceding operations for each machining operation. If a machining operation having no preceding operation is encountered, then it is assigned as the first operation of the respective setup. A sample rule for finding preceding operations  $n2$  and  $n3$  for an operation  $n1$  based on precedence relations is as follows:

```
(Defrule::preceding-operation
?f1<-(operation(number ?n1)(type ?type)(TAD_cluster ?TAD)(preceding_opn ?n2))
?f2<-(operation(number ?n1)(type ?type)(TAD_cluster ?TAD)(preceding_opn ?n3))
=>(assert(operation(number ?n1)(type ?type)(TAD_cluster ?TAD)
(preceding_operation ?n2 ?n3))
```

The rule states that if there are two facts (fact identifiers  $?f1$   $?f2$ ) about an operation  $n1$  having preceding operations  $n2$  and  $n3$ , then a new fact is generated stating that operation  $n1$  has  $n2$  and  $n3$  as preceding operations.

Next, a set of rules has been developed to determine the sequence of operations within a setup by scanning all the operation facts from the database (original ones and the new facts generated by firing of the rules) and then assigning each operation to one of the two setups in order of their precedence. The scanning of operation facts is continued until all the machining operations are assigned to one of the setups. A machining operation is assigned to a setup only if all its preceding operations have been assigned. Example of a rule for operation sequencing in Setup-1 is as follows:

```
(Defrule::sequence-setup-1
?f1<- (operation (number ?n1)(type mill)(preceding_operation ?n2))
?f2<- (operation (number ?n2)(setup setup-1))
=> (bind ?operation-setup-1 (fact-slot-value ?f1 number))
(bind ?*sequence-setup-1-feature-cluster*(create$ ?operation-setup-1))
```

The rule states that if an operation  $n1$  (fact identifier  $?f1$ ) has a preceding operation  $n2$  (fact identifier  $?f2$ ), and  $n2$  is assigned to setup-1, then operation  $n1$  is also

assigned to setup-1 in the proper sequence considering all other conditions are satisfied. Thus, using the precedence constraint information and developed rules as discussed above, a feasible sequence of machining operations within each setup is automatically generated. The machining operations are arranged in the sequential order in which they are to be performed.

#### 3.4.2.4 Datum Selection for Each Setup

Once the setups are formed and the operations within a setup are sequenced, the setup datums are to be selected. The decision on selecting suitable datums for each setup depends on various factors like feature tolerance relationships, surface area of a face, its orientation, symmetry, and surface quality. Most of the previous researchers have given priority to any one of the above factors. Tolerance relations with other features and maximum area face are the most widely used criteria for selecting datum. However, selection of proper datum is very important for tolerance requirements and functionality of the part. To select datum for a setup, first all the faces of the part are identified. The faces having an orientation different from the faces being machined in that setup are sorted out. The priorities used for selection of primary datum in the present approach are as follows:

- Priority 1: The face having the maximum number of tolerance relations with other features is selected as primary datum.
- Priority 2: The largest surface area face is selected as primary datum.
- Priority 3: Machined faces are selected as primary datum.

A sample rule for selecting primary datum based on tolerance relations for Setup-1 is shown below. It states that there is a machining operation (fact identifier ?f1) to make a feature hole (fact identifier ?f2) having TAD as TAD6. The operation has tolerance relations with more than one feature and it has the tightest tolerance relation with a feature face (fact identifier ?f3) with TAD as TAD3. Therefore, the face (fact identifier ?f3) is selected as primary datum for Setup-1.

*(Defrule::selecting-primary-datum-for-setup-1  
?f1<-(operation(on\_feature ?on\_feature)*

```
?f2<-(feature(number ?on_feature)(name HOLE) (TAD TAD6))
?f3<-(feature(name FACE)(TAD TAD3))
(test (>= (length$ (fact-slot-value ?f1 tolerance)) 2))
(operation (on_feature =(feature-with-tightest-tolerance ?f3)) (TAD TAD3))
=> (assert(=PRIMARY-DATUM-SETUP-1(feature-with-tightest-tolerance ?f3))
```

Another priority for selecting datum is surface area of a face. A rule for selecting datum based on maximum area face is shown below. It states that there is a machining operation (fact identifier ?f1) on a feature face (fact identifier ?f2) having TAD as TAD6. A function ‘face-having-largest-area-for-primary-datum’ compares the areas of the different faces and returns the fact identifier of the face having maximum area. The identified face has the largest area among the candidate faces for datum and it is selected as primary datum for Setup-1.

```
(Defrule::selecting-primary-datum-for-setup-2
?f1<-(operation(on_feature ?number)(TAD TAD6))
?f2<-(feature(name FACE)(number ?number)(TAD TAD6))
=> (if (= ?number ?*face-having-largest-area-for-primary-datum*)
then (duplicate ?f2 (name PRIMARY-DATUM-SETUP-1)))
```

For selecting secondary datum, all the faces perpendicular to the primary datum are considered and the largest face is selected as the secondary datum. The following is a sample rule for selecting secondary datum for Setup-1.

```
(Defrule::selecting-secondary-datum-for-setup-1
?f1<-(feature(name PRIMARY-DATUM-SETUP-1)(number ?n1))
?f2<-(feature(name FACE)(number ?n2)(perpendicular_to $? ?n1 $?))
=> (if (= ?n2 ?*face-having-largest-area-for-secondary-datum*)
then (duplicate ?f2 (name SECONDARY-DATUM-SETUP-1)))
```

The tertiary datum is the largest face which is perpendicular to both primary and secondary datum. A sample rule for selecting tertiary datum is shown below.

```
(Defrule::selecting-tertiary-datum-for-setup-1
?f1<-(feature(name PRIMARY-DATUM-SETUP-1)(number ?n1))
?f2<-(feature(name SECONDARY-DATUM-SETUP-1)(number ?n2))
?f3<-(feature(name FACE)(number ?n3)(perpendicular_to $? ?n1 $? ?n2 $?))
=> (if (= ?n3 ?*face-having-largest-area-for-tertiary-datum*)
    then (duplicate ?f3 (name TERTIARY-DATUM-SETUP-1)))
```

All the above knowledge-base rules have been coded using the language format of the CLIPS expert system shell and saved in the knowledge-base as files with the extension .clp. At the time of execution of the expert system program, the rules are to be loaded from the knowledge-base files into the expert system environment. The modular nature of the proposed expert system makes it easier to incorporate knowledge and expand the knowledge-base by incremental development. The rules are easily understandable and editable by the user.

### 3.4.3 Fixturing Information Generation Module

The proposed setup planning expert system has a fixturing information generation module which provides some essential fixturing information to the fixture planner. This module provides the information on machining forces, required clamping forces, recommended process parameters, approximate optimal locator and clamp layout, and sizes of the locators and clamps in addition to normal setup information. The fixturing information generation module contains a machining force calculation module, locator and clamp layout optimization module, workpiece-fixture contact module and a locator and clamp design module. The detail of incorporating fixturing requirements in the setup planning expert system is discussed in Chapter 6.

### 3.4.4 Provision for Uncertainty and Feedback

Uncertainty of the knowledge is one important factor which affects the final outcome of a setup planning problem. Considering the fact that setup planning has to be carried out in an environment of uncertainty particularly in feature precedence

relations, datum selection, and uncertainties associated with material properties, a fuzzy set based method is proposed to deal with these uncertainties. A strategy for adaptive learning from the feedback received from actual production stage is proposed. The proposed approach enables the setup planning system to modify and adapt the knowledge-base to the actual situations on the shop floor. This module is discussed in detail in Chapter 4.

### **3.4.5 The Inference Engine**

The inference engine contains and realizes the decision making strategy. It is that part of the CLIPS expert system shell which is already programmed and ready for use. The inference engine is separated from the knowledge-base and is an independent module that makes the expert system more flexible. The inference mechanism in CLIPS expert system shell is based on forward chaining strategy where a line of reasoning is formed by chaining the IF-THEN rules in the knowledge-base to arrive at a decision. The feature and operation facts of a part to be machined are stored as data files and loaded into the CLIPS environment along with the rules from the knowledge-base module. The inference engine draws inference by deciding which rules are satisfied by facts, assign priority to the rules, and execute the rules with the highest priority.

### **3.4.6 The User Interface**

The user interface is that part of the CLIPS expert system shell which provides the mechanism by which the user interacts with the expert system. It provides an easy access for the user to the expert system through a communication interface. The information on the various attributes of the features and the machining operations of a component, information on machine tools and cutting tools, and material properties of the workpiece material, locating and clamping element materials are to be given as input by the user. Additional information and some required on-the-spot information on the shop floor can also be provided interactively. The user interface allows the user to perform various tasks, such as creating and editing the database and knowledge-base files using a text editor, saving the text files, loading the saved

files into CLIPS environment, and executing the expert system program. It also provides commands for viewing the current state of the system, keeping track on the steps of the execution, recording the number of rules fired, time taken and so on. Output of the final results and decisions are also communicated to the user through this interface.

A simple explanation facility is also provided in the CLIPS expert system shell. The explanation facility displays the reason behind firing a certain rule and is helpful in debugging the program. For example, it displays all the facts from the database which satisfies the IF part of a certain rule from the knowledge-base. It is helpful in debugging the knowledge-base of the expert system.

By following the methodology presented above, the CLIPS expert system shell is used to develop a setup planning expert system for machining of prismatic parts. The expert system is capable of automatically performing different setup planning tasks. The setup planning expert system automatically generates, as output, the number and the sequence of setups needed to machine a component, the machining operations to be carried out in each setup in their proper sequence, datum for each setup, required clamping forces, recommended process parameters, approximate optimal locator and clamp layout, and sizes of the locators and clamps. After development of the expert system program, it is important to validate its performance on different parts. Accordingly, the performance of the developed setup planning expert system is validated on a variety of parts. The illustrative examples are presented in Chapter 7.

### 3.5 Summary

In this chapter, an overview of the proposed setup planning expert system is discussed. Brief background knowledge on expert systems is presented describing the essential components of an expert system. CLIPS, an expert system shell is used to develop the setup planning system in the present work. Different structures of CLIPS are described in detail with examples. CLIPS contains a built-in inference engine, a user interface, a set of knowledge representation structures and facilities to interface with external systems.

Next, different modules of the setup planning expert system are described. It contains a database, a knowledge-base, a fixturing information generation module, a module for uncertainty and feedback, inference engine and a user interface. The development steps of the database and the knowledge-base are discussed thoroughly with examples. The database contains the detailed information on the features, machining operations, machine tools, cutting tools and material properties represented in the form of Deftemplate. There are different sets of rules developed and stored in the knowledge-base for solving setup planning problem. There are rules for precedence constraint generation, feature clustering, setup formation, operation sequencing and datum selection developed based on knowledge gathered from experts, books and actual shop floor observations. Sample rule for each case is given and explained in detail. The inference engine in CLIPS shell works on forward chaining strategy.

A brief introduction to uncertainty and feedback module and fixturing information generation module is presented. Uncertainty and feedback module and fixturing information generation module are discussed in detail in Chapter 4 and Chapter 6 respectively.



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## A Fuzzy Set Based Methodology for Updating the Knowledge-base Based on Shop Floor Feedback

### 4.1 Introduction

Uncertainty of the acquired knowledge is an important factor in the knowledge-based systems which affect the performance of the systems. In knowledge-based systems, experts' knowledge is acquired from different sources and represented as domain knowledge in the form of IF-THEN rules. However, incomplete information, imprecision and vagueness in the acquired knowledge lead to uncertainty. The performance of knowledge-based systems depends to a large extent on the way uncertainty is managed by the system. Considering the fact that setup planning has to be carried out in an environment of uncertainty, a fuzzy set based approach is used to deal with uncertainty in this work. Uncertainty in the knowledge, particularly in feature precedence relations and datum selection are considered. Moreover, the proposed setup planning system can modify and adapt the knowledge-base based on the feedback received from the actual machining conditions on the shop floor. Traditional software systems used for automating setup planning are static in nature and they do not respond to the changes in the situation. It is necessary and important for such experts systems to keep learning and evolving from experience.

In this chapter, a background of fuzzy sets is presented in Section 4.2. In Section 4.3, the developed strategy for uncertainty management in the knowledge-base of the setup planning expert system is discussed. The methodology for updating the knowledge-base based on the feedback from the shop floor is presented in Section 4.4. In Section 4.5, a methodology is presented for fine tuning the initial membership grades assigned by an expert for fuzzy variables. Fine tuning of the

initial expert's estimates of the membership grades enhances the system performance. Finally, a summary is presented in Section 4.6.

## 4.2 A Background of Fuzzy Sets

Fuzzy set theory was first proposed by Zadeh [1965]. Fuzzy set theory derives its motivation from approximate reasoning. With the introduction of fuzzy set theory, the scope of traditional mathematical approach is widened to accommodate partial truth or uncertainty. Transition from crisp (true/false) mathematics to fuzzy mathematics by means of fuzzy set theory has enabled computing with natural language. In fuzzy sets, the precise value of a variable is replaced by a linguistic variable. Linguistic variables can have linguistic values. If *temperature* is a linguistic variable, then its linguistic values can be *high*, *low* and *moderate*. These values are represented by fuzzy sets. Fuzzy sets can be used in human decision making process to draw conclusions from vague, ambiguous or imprecise information.

A set is a collection of elements. In a crisp set, the elements of the universe are either a member or non-member of a set. Fuzzy sets are those sets whose boundaries are vaguely defined. Fuzzy set theory may be considered as an extension of classical set theory. Classical set theory deals with crisp sets with sharply defined boundaries, whereas fuzzy set theory is concerned with fuzzy sets whose boundaries are fuzzy. The benefit of replacing the sharply defined boundaries with the fuzzy boundaries is the strength in solving real world problems, which involve some degree of imprecision and fuzziness. An element of the universe may be a member of a fuzzy set to varying degrees. The same element can be a member of different fuzzy sets with different degree of membership. Unlike classical set theory, fuzzy set theory is flexible and focuses on the degree of being a member of a set. In a fuzzy set, the members are allowed to have any positive membership grade between 0 and 1. The membership grade is defined as the degree of being a member of a fuzzy set. Membership grades are subjective, but not arbitrary. For example, consider that there are two fuzzy sets 'young man' and 'old man'. A 25 years old person may be

given a membership grade of 0.8 in the set of ‘young man’ by one expert and 0.9 in the same set by another expert. The same person may be given 0.2 and 0.3 membership grades in the set of ‘old man’ by the two experts respectively. Both the values of membership grades (0.8/0.9 and 0.2/0.3) are considered reasonable. The slight difference is due to the difference in perception of the two experts. However, in a crisp set, the person will have membership grades 1 and 0 in the sets of ‘young man’ and ‘old man’ respectively. Similarly, a 15 years old boy may have 0.4 (say) membership grade in the set of ‘young man’, and 0.1 (say) membership grade in the set of ‘old man’. In a fuzzy set, a membership grade 1 indicates full membership and 0 indicates full non-membership in the set. Any other membership grade between 0 and 1 indicates partial membership of the element in the set. Some skill is needed to form a fuzzy set that properly represents the linguistic name assigned to the fuzzy set. For a background on fuzzy sets and its various applications, one can refer to Berkan and Trubatch [1997] and Dixit and Dixit [2008].

#### 4.2.1 Mathematical Definition of Fuzzy Sets

The process by which the elements from a universal set  $X$  are determined to be either members or non-members of a crisp set can be defined by a characteristic or discrimination function. For a given crisp set  $A$ , this function assigns a value  $\mu_A(x)$  to every  $x \in X$  such that

$$\mu_A(x) = \begin{cases} 1 & \text{if and only if } x \in A, \\ 0 & \text{if and only if } x \notin A. \end{cases} \quad (4.1)$$

Thus the function maps elements of the universal set  $X$  to the set containing 0 and 1. This is indicated by

$$\mu_A : X \rightarrow \{0,1\}. \quad (4.2)$$

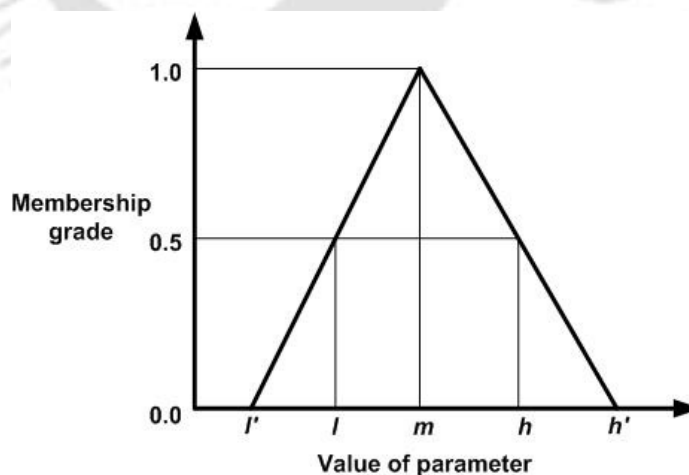
This kind of function can be generalized such that the values assigned to the elements of the universal set  $X$  fall within a specified range. These values are called membership grades of the elements in the set. Larger values denote higher degree of membership and vice versa. Such a function is called a membership function  $\mu_A$  by which a fuzzy set  $A$  is usually defined. The fuzzy membership function is indicated by

$$\mu_A : X \rightarrow [0,1] \quad (4.3)$$

where  $[0,1]$  denotes the interval of real numbers from 0 to 1 (*e.g.* 0.1, 0.4, 0.6, 0.9, *etc.*), inclusively.

#### 4.2.2 Determination of Membership Functions

To assign suitable values of membership grades and constructing the membership function is one of the most challenging tasks of fuzzy set theory. Design of fuzzy membership functions greatly affects a fuzzy set based inference system. Membership functions are subjective. Normally an expert's opinion is sought to construct the membership function for a fuzzy variable. The geometrical shape of the membership function characterizes the uncertainty in the corresponding fuzzy variable. There are different types of membership function, *e.g.* triangular, trapezoidal, Gaussian function, S-function,  $\pi$ -function, *etc.* For ease of computation, linear membership functions such as triangular and trapezoidal functions are preferred. However, in order to mimic real life problem, non-linear membership functions may be used. A typical triangular membership function is shown in Figure 4.1. It is constructed by taking the membership grade as 1.0 at most likely ( $m$ ) and 0.5 at low ( $l$ ) and high ( $h$ ) estimates of a fuzzy parameter. The vertices  $l'$  and  $h'$  denote the extreme low and extreme high estimates of the parameter.



**Figure 4.1.** A triangular membership function

### 4.2.3 Fuzzy Set Operations

Fuzzy sets have been extensively used in decision making by employing various operations on fuzzy set theory. Fuzzy union ( $A \cup B$ ) and fuzzy intersection ( $A \cap B$ ) between two fuzzy sets  $A$  and  $B$  are the two most commonly used fuzzy operations. The union of two fuzzy sets  $A$  and  $B$ , *i.e.*,  $A \cup B$  is defined as a set in which each element has a membership grade equal to the maximum of its membership grade in  $A$  and  $B$ . Similarly, the intersection of two fuzzy sets  $A$  and  $B$ , *i.e.*,  $A \cap B$  is defined as a set in which each element has a membership grade equal to the minimum of its membership grade in  $A$  and  $B$ . Fuzzy union and intersection operations are expressed as

$$\begin{aligned}\mu_{A \cup B} &= \max\{\mu_A, \mu_B\}, \\ \mu_{A \cap B} &= \min\{\mu_A, \mu_B\}.\end{aligned}\tag{4.4}$$

Fuzzy complement, fuzzy absolute difference, fuzzy product are some more examples of fuzzy set operations.

Fuzzy set operations are useful in taking decisions in the presence of conflicting and incommensurable objectives [Dixit, 2010]. For example, consider that a certain product requires functionality as well as aesthetic appeal as its attributes. Now, if the product has a membership grade of  $\mu_1$  in the set of ‘functionality’ and a membership grade of  $\mu_2$  in the set of ‘aesthetic appeal’, then the overall membership grade  $\mu_o$  in the set of ‘suitable product’ can be found as

$$\mu_o = \min(\mu_1, \mu_2)\tag{4.5}$$

Here the overall performance of the product is dependent on the most poorly performing attribute. This type of strategy is called non-compensating strategy. An overall membership grade based on a compensating strategy may be defined as

$$\mu_o = \sqrt{\mu_1 \mu_2}\tag{4.6}$$

A weighted combination of the two strategies may also be considered. If the membership grades of a product in  $n$  different objectives are  $\mu_1, \mu_2, \dots, \mu_n$ , then overall membership grade is defined as

$$\mu_o = (1 - \alpha) \min(\mu_1, \mu_2, \dots, \mu_n) + \alpha \sqrt[n]{\mu_1 \mu_2 \dots \mu_n},\tag{4.7}$$

where  $\alpha$  is a weight factor. Putting  $\alpha=1$  in Equation (4.7), a pure compensating strategy is obtained and  $\alpha=0$  in Equation (4.7) provides a pure non-compensating strategy.

#### 4.2.4 Fuzzy Arithmetic

A prominent branch of fuzzy set theory is fuzzy arithmetic which deals with the fuzzy numbers. Many of the process variables encountered in real life problems are imprecise and uncertain and considered fuzzy. They are best represented by fuzzy numbers. For example, yield stress, coefficient of friction, modulus of elasticity, *etc.* can be represented by fuzzy numbers. Fuzzy arithmetic can be employed to compute the output as a fuzzy variable. A fuzzy number is a generalization of an interval number. An interval number is specified by an upper and a lower limit. The interval numbers are used when the value of a variable is expected to lie in a range. A fuzzy number consists of the different interval numbers at different membership grades. Mathematical operations of fuzzy sets are defined at an  $\alpha$ -cut. An  $\alpha$ -cut of a membership function  $\mu(x)$  is the set of all  $x$  such that  $\mu(x)$  is greater or equal to the value of  $\alpha$ . Thus, at a particular  $\alpha$ -cut, an interval number is obtained corresponding to the interval number at the membership grade of  $\alpha$ . Each fuzzy number has an interval with lower and upper limits. For example, a typical fuzzy number  $A$  can be represented as

$$A_{\alpha} = [a_1^{\alpha}, a_2^{\alpha}], \quad (4.8)$$

where  $A_{\alpha}$  is the interval corresponding to the membership grade of  $\alpha$  and  $a_1^{\alpha}$  and  $a_2^{\alpha}$  are the lower and upper limits of the interval. For example Young's modulus of elasticity of steel may be given by the fuzzy number (190, 210) GPa at  $\alpha$ -cut of 0.7 (say). Some of the fuzzy arithmetic operations are shown below. Here  $A_{\alpha}$  and  $B_{\alpha}$  are two fuzzy numbers at an  $\alpha$ -cut.

##### Fuzzy addition

$$A_{\alpha}(+)B_{\alpha} = [a_1^{\alpha}, a_2^{\alpha}](+)[b_1^{\alpha}, b_2^{\alpha}] = [a_1^{\alpha} + b_1^{\alpha}, a_2^{\alpha} + b_2^{\alpha}]. \quad (4.9)$$

##### Fuzzy subtraction

$$A_{\alpha}(-)B_{\alpha} = [a_1^{\alpha}, a_2^{\alpha}](-)[b_1^{\alpha}, b_2^{\alpha}] = [a_1^{\alpha} - b_2^{\alpha}, a_2^{\alpha} - b_1^{\alpha}]. \quad (4.10)$$

### Fuzzy multiplication

$$A_\alpha(\times)B_\alpha = [a_1^\alpha, a_2^\alpha](\times)[b_1^\alpha, b_2^\alpha] = [a_1^\alpha \times b_1^\alpha, a_2^\alpha \times b_2^\alpha]. \quad (4.11)$$

### Fuzzy division

$$A_\alpha(\div)B_\alpha = [a_1^\alpha, a_2^\alpha](\div)[b_1^\alpha, b_2^\alpha] = [a_1^\alpha \div b_2^\alpha, a_2^\alpha \div b_1^\alpha]. \quad (4.12)$$

## 4.2.5 Linguistic Variables and Hedges

Fuzzy set theory uses natural language and thus deals with linguistic variables. Linguistic variables can have linguistic values. If *age* is a linguistic variable, then its linguistic values can be *young*, *middle-aged* and *old*. A linguistic variable is often associated with fuzzy set quantifiers called hedges. The function of hedges is to modify the membership function of an already defined fuzzy variable. The examples of some hedges are *very*, *usually*, *fair*, *quite*, *etc.* Linguistic value of a fuzzy set can be modified by applying a hedge as an operator on the fuzzy set. For example, the hedge *very* performs concentration by reducing the membership values of the members and creates a new subset as shown below:

$$\mu_A^{\text{very}}(x) = [\mu_A(x)]^2 \quad (4.13)$$

Similarly, *more or less*, *i.e.* *fair* performs dilation and increases the degree of membership of fuzzy variables as follows:

$$\mu_A^{\text{more or less}}(x) = \sqrt{\mu_A(x)} \quad (4.14)$$

Thus, using linguistic hedges, computation can be done using natural language. Usually, a fuzzy set based model is built by using expert knowledge in the form of linguistic rules. Fuzzy set theory, compared to other mathematical theories is easily adaptable. Fuzzy sets allow possible deviations and inexactness in defining an element. Therefore fuzzy set representation suits well the uncertainties encountered in practical life. This quality makes fuzzy set theory a valuable mathematical tool.

## 4.3 Strategy for Uncertainty Management in the Knowledge-base

The knowledge-base in an expert system contains the domain specific knowledge that is used to solve problems. The most common form of representing

the knowledge is IF–THEN rules. The knowledge for formulating the rules is based on heuristic and expert knowledge from various sources such as interviews with experts and skilled machinists, handbooks and textbooks. However, there may be uncertainty in the collected knowledge which affects the final outcome of the expert system. Decision making in setup planning problem involves the use of uncertain knowledge to a large extent. This aspect is not given its due importance in setup planning approaches found in the literature. Incomplete information, imprecision and vagueness in the acquired knowledge lead to uncertainty. In addition, rules themselves can be uncertain or the expert may be uncertain of the rule itself. For example, precedence relation between machining of two features may depend on many uncertain factors. This fact was realized by Ong and Nee [1994] as early as 1994. The authors applied fuzzy set theory to deal with the uncertainty associated with the precedence relations. They used the concept of feature dependency grades to deal with uncertain feature relations. The dependency grade is basically a membership grade ranging from 0 to 1. If the dependency grade from feature A to feature B is 1, then feature A can be machined only after machining feature B. If the dependency grade is less than 1, then it is preferred that A should be machined before B, the strength of preference being proportional to dependency grade. However, the authors did not consider the uncertainty associated with other parts of the knowledge-base in setup planning, for example selection of datum.

Another important aspect observed from the literature review on setup planning is that most of the research efforts considering uncertainty dealt with the uncertainty on the shop floor, *viz.* resource and capacity constraints, machine breakdown, and tool failure, but not the uncertainty in the knowledge-base [Masood and Srihari, 1993; Zhang and Huang, 1994; Usher and Farnandes, 1996; and Wong *et al.*, 2003]. Moreover, the available strategies are incapable of handling linguistic uncertainty arising from vagueness of human knowledge, *e.g.* defining variables in terms of ‘high’, ‘low’, ‘medium’, *etc.* The efforts dealing with the uncertainty in the knowledge-base are limited, although there are efforts considering the uncertainty in the shop floor resources. Generation of a feasible and optimal setup plan depends to a large extent on the way uncertainty is managed by the system.

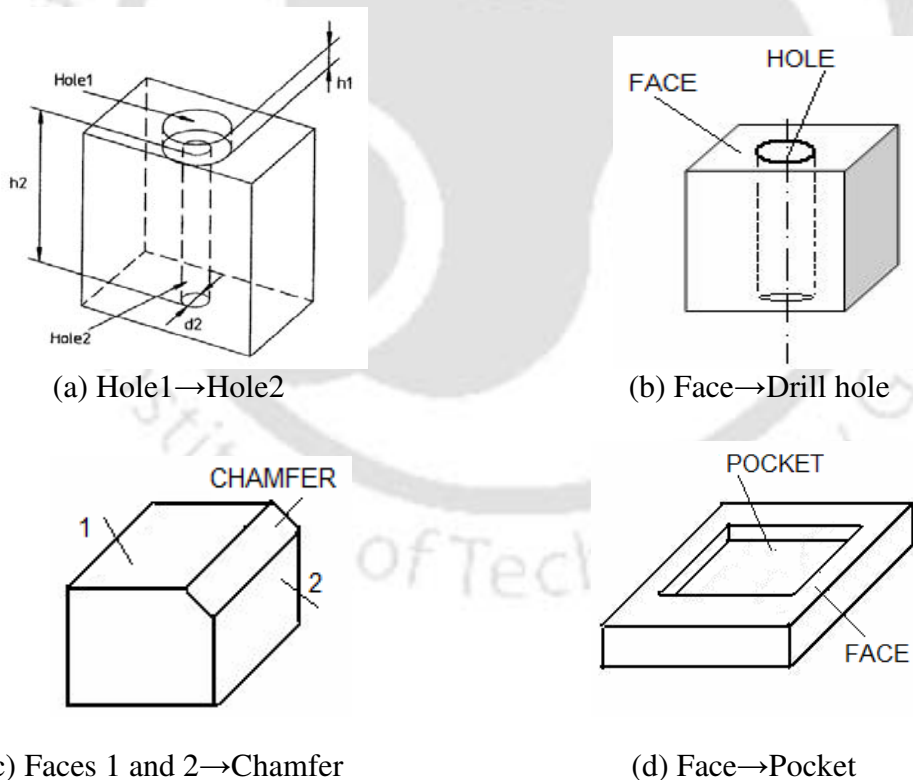
The present work uses the concept of Ong and Nee [1994] and extends it further. A fuzzy set based approach is proposed to manage uncertainty in the knowledge-base with fuzzy membership grades. It deals with the uncertainty among the feature precedence relations as well as the uncertainty in datum selection. The proposed fuzzy set based setup planning system is capable of updating itself based on shop floor feedback during actual production. Thus, it keeps evolving with experience.

#### 4.3.1 Uncertainty in the Feature Precedence Relations

Feature precedence relations arise from basic manufacturing principles and feature interactions. A precedence relation between two features F1 and F2, denoted as  $F1 \rightarrow F2$ , implies that F2 cannot be machined until the machining of F1 is complete. Different precedence relations are obtained due to area/volume feature interactions, tolerance relations, feature accessibility, tool interaction, fixturing interaction, datum/reference/locating requirements, and constraint of good manufacturing practice. Feature precedence relations are discussed in detail in Section 3.4.2.1, Chapter 3. The optimal machining sequence depends on the precedence relations to a large extent. Some precedence relations such as 'datum features, reference features, and parent features are to be machined first' have no uncertainty in them. They form the basis for definite rules. However, there may be uncertainty about some assumed precedence relations. The validity of these precedence relations are to be reviewed keeping in mind the other related factors such as machining cost and time, work material properties, the required surface finish, *etc.* Figure 4.2. shows some uncertain precedence relations.

Figure 4.2 (a) shows the precedence relation for drilling two concentric holes of different diameters and depth. Applying good manufacturing practice, drilling of smaller depth hole precedes the longer depth hole. However, the precedence relation is not certain as the decision depends on many related factors like hole dimensions, ease of access, tool used, possibility of tool damage, material properties, cutting parameters, *etc.* In some cases drilling followed by counter boring is preferred. Similarly, Figures 4.2 (b)–(d) show the precedence of machining the faces first and

then drilling/chamfering/machining pocket. However, some ambiguity arises in this type of relations. Some similar type of uncertain relations may be ‘machine the face first and then machine a slot/step/pocket on the face’. As some material is removed in the shape of a slot/step/pocket, it is not economical to go for machining the whole face. Decision is based on fuzzy knowledge. The surface finish required, cost and time of machining, work material property, burr formation during drilling and milling, process parameters, tool geometry and tool changes are some of the related factors that affect the decision. The certainty of these precedence relations is to be reviewed keeping in mind the related factors. As optimal machining sequence depends on precedence relations, an approach for evaluation of these relations is very important. In the proposed approach for setup planning, the validity of the precedence relations can be evaluated with a fuzzy set based method.



**Figure 4.2.** Uncertain feature precedence relations

Figure (a) presented with permission from Zhang *et al.*, Copyright[1995] Elsevier.

The precedence relation shown in Figure 4.2 (b), 'face and then drill hole' is taken as example to explain the fuzzy set based methodology for uncertainty management. The relation 'face and then drill hole' is based on uncertain knowledge and leads to ambiguity. If there is burr formation during drilling, then it would be better to drill hole first and then face. Burrs are produced during drilling on both entry and exit surfaces of the workpiece due to plastic deformation of the workpiece material. Burrs are unwanted elements and burr removal involves extra cost. However, there is a possibility of burrs of negligible size which can be accepted, and facing can precede drilling in such cases. The decision depends on many other factors like work material property (ductile or brittle), the required surface finish, process parameters, tool used, total machining time and cost, *etc.* Significant amount of research has been devoted towards prediction and control of burr formation in drilling. It is evident from the literature that various parameters affecting burr formation in drilling are material properties, process parameters and drill geometry [Stein and Dornfeld, 1997; Min *et al.*, 2001; Pena *et al.*, 2005; Aramendi *et al.*, 2008; Lauderbaugh, 2009; Ko and Lee, 2001; Ko *et al.*, 2003]. Feed rate is found to be a significant factor for burr formation in these studies. Burr size is highly affected by the ductility of the workpiece material. It is observed that burr height increases with increasing ductility. Drill geometry also has a significant effect on burr shape and size [Min *et al.*, 2001; Lauderbaugh, 2009; Ko and Lee, 2001; Ko *et al.*, 2003]. Optimization of drill geometry can minimize burr size. From the review of literature, it is observed that ductility, feed rate and tool geometry are three significant parameters which affect burr formation in drilling. In the present work, burr height is considered as a function of these three parameters. The following fuzzy rules can be formulated regarding burr formation in drilling:

*IF workpiece material is ductile THEN burr height is more.*

*IF drill point angle is  $118^\circ$  THEN burr height is more.*

*IF feed rate is high THEN burr height is more.*

Here ductility, tool geometry and feed rate are the fuzzy input parameters affecting the burr height in drilling. The input parameters may have varying effect on the

consequent part of a rule. In case of burr formation in drilling, the ductility of the workpiece material plays a dominant role compared to the other two parameters. To take into account the varying effect of the input parameters, the following relation is adopted. If  $\mu_{\text{duc}}$ ,  $\mu_{\text{tool}}$  and  $\mu_{\text{feedrate}}$  are the individual membership grades (ranging from 0 to 1) assigned to ductility of the workpiece material, tool geometry and feed rate respectively, then it is proposed to calculate the overall computed membership grade  $\mu_c$  for burr height as

$$\mu_c = \mu_{\text{duc}} \left\{ \left( \frac{\mu_{\text{tool}} + \mu_{\text{feedrate}}}{2} \right) \wedge 1 \right\}, \quad (4.15)$$

which asserts the greater effect of ductility and combined additive effect of tool geometry and feed rate on burr height in drilling. Note that  $(a \wedge b)$  indicates the minimum of  $a$  and  $b$ . The ambiguous precedence rules can be written as

Rule 1: Drill hole  $\rightarrow$  Face

Rule 2: Face  $\rightarrow$  Drill hole

The decision to follow Rule 1 or Rule 2 depends on many factors. The following method can be adopted for different situations.

- If for a particular combination of workpiece material, tool and feed rate, the value of  $\mu_c$  is low, there will be no burr formation during drilling and therefore no precedence relation will be required. Any one of the two rules can be followed.
- If the value of  $\mu_c$  is high, there will be greater chance of burr formation of considerable size and therefore precedence relation will be required. In such cases, selection of Rule 1 or Rule 2 will depend on the cost factor. There can be two options: machining without burr (following Rule 1) or machining with burrs (following Rule 2) followed by deburring techniques to remove burrs. The rule providing lower cost will be chosen.
- If the value of  $\mu_c$  is neither high nor low, then the decision to follow Rule 1 or Rule 2 largely depends on the feedback received from the shop floor during actual machining stage. Certain performance measures such as presence of burrs,

number of tool changes, surface finish, and total machining time are to be monitored on the shop floor at the time of actual machining and decision is to be taken based on these feedbacks. This can be done by the quality control or inspection engineer on the shop floor.

The fuzzy input parameters ductility, tool geometry and feed rate are assigned fuzzy membership grades  $\mu_{duc}$ ,  $\mu_{tool}$  and  $\mu_{feedrate}$  as given in Table 4.1. Workpiece material is graded based on their ductility. Tool geometry is graded based on the availability of the proper drill. An experimental study conducted by Ko *et al.* [2003] showed that conventional drills with 118° drill point angle produce higher size burrs compared to 130° drill point angle and step drill with an optimum step angle of 75° (or lower) produce smaller size burrs compared to conventional drills. Feed rate is graded based on the range of feed rate considered (50 mm/min to 300 mm/min). Expert's opinion is sought to assign the membership grades of these input parameters.

**Table 4.1.** Membership grades for ductility, tool geometry and feed rate

Material	$\mu_{duc}$	Availability of drill	$\mu_{tool}$	Feed rate (mm/min)	$\mu_{feedrate}$
Ductile like aluminum	0.9	118° point angle conventional drill	0.9	Very low 50-100	0.2
Low carbon steel like mild steel	0.7	130° point angle conventional drill	0.8	Low 100-150	0.3
High carbon steel	0.4	130° step angle step drill	0.4	Medium 150-200	0.5
Alloy steel	0.3	75° step angle step drill	0.3	High 200-250	0.7
Brittle like cast iron	0.2	60° step angle step drill	0.2	Very high 250-300	0.8

Overall membership grade for burr height in drilling is calculated from Equation (4.15). There may be a number of cases of different combinations of workpiece material, tool and feed rate used. Some hypothetical cases are discussed here to explain the strategy for uncertainty management.

Case 1: If the material is aluminium, tool used is 118° conventional drill and feed rate is very high,  $\mu_c = 0.9 \left\{ \left( \frac{0.9+0.8}{2} \right) \wedge 1 \right\} = 0.80$ , indicating that there is great chance of burr formation. Drilling should be done prior to facing for a better surface finish.

Case 2: If the material is low carbon steel, tool used is 130° step drill and feed rate is medium,  $\mu_c = 0.7 \left\{ \left( \frac{0.4+0.5}{2} \right) \wedge 1 \right\} = 0.32$ , indicating that chance of burr formation is low. Therefore, facing can precede drilling and Rule 2 can be followed. However, actual drilling process should be monitored on the shop floor to check for burr formation.

Case 3: If the material is low carbon steel, tool used is 130° point angle conventional drill and feed rate is medium,  $\mu_c = 0.7 \left\{ \left( \frac{0.8+0.5}{2} \right) \wedge 1 \right\} = 0.45$ . As the value of  $\mu_c$  is neither low nor high, the decision to use Rule 1 or Rule 2 depends on the feedback received from the shop floor.

Case 4: If the material is high carbon steel, tool used is 75° step angle step drill and feed rate is low,  $\mu_c = 0.4 \left\{ \left( \frac{0.3+0.3}{2} \right) \wedge 1 \right\} = 0.12$ , indicating that there is negligible amount of burr formation. Therefore facing can precede drilling.

If the value of  $\mu_c$  is small (<0.5), chances of burr formation is less and Rule 2 can be followed subject to shop floor feedback in the marginal cases. However, for higher values of  $\mu_c$  (>0.8), there is a greater chance of burr formation of considerable size and the associated cost of machining is to be considered. The rule providing lower cost will be selected.

#### 4.3.2 Uncertainty in the Datum Selection

The decision on selecting suitable datum for each setup depends on various factors like feature tolerance relationships, surface area of a face, its orientation, symmetry, and surface quality. Most of the previous researchers have given priority

to any one of the above factors. Tolerance relations with other features and maximum area face are the most widely used criteria for selecting datum [Mei *et al.* 1995; Huang and Xu, 2003; Senthil Kumar *et al.* 1992; Gologlu, 2004]. However, selection of proper datum is very important for tolerance requirements and functionality of the part. As choosing the proper criteria for selecting datum is based on uncertain knowledge, fuzzy set is used to deal with the uncertainty associated with datum selection in the proposed approach. To select datum for a setup, first all the faces of the part are identified. The faces having an orientation different from the faces being machined in that setup are sorted out. Criteria considered for datum selection are tolerance relations with other features, area of the candidate face and the surface quality of the face. The criterion tolerance relation means the number of tolerance relations with other features and the type *i.e.*, critical/tightest tolerance relation. However, individual objectives of these criteria are conflicting and incommensurable. Each objective is to be satisfied to a certain minimum level. Fuzzy set operations are very useful in decision making in cases where conflicting and incommensurable objectives are to be satisfied. The strategy adopted to achieve the overall objective is as follows. If  $\mu_{gt}$ ,  $\mu_{gsa}$ , and  $\mu_{gsq}$  are the individual fuzzy membership grades for good tolerance relation, good surface area and good surface quality for a particular candidate face for datum, then the overall membership grade for the face is given by

$$\mu_{o_{datum}} = \min (\mu_{gt}, \mu_{gsa}, \mu_{gsq}) \quad (4.16)$$

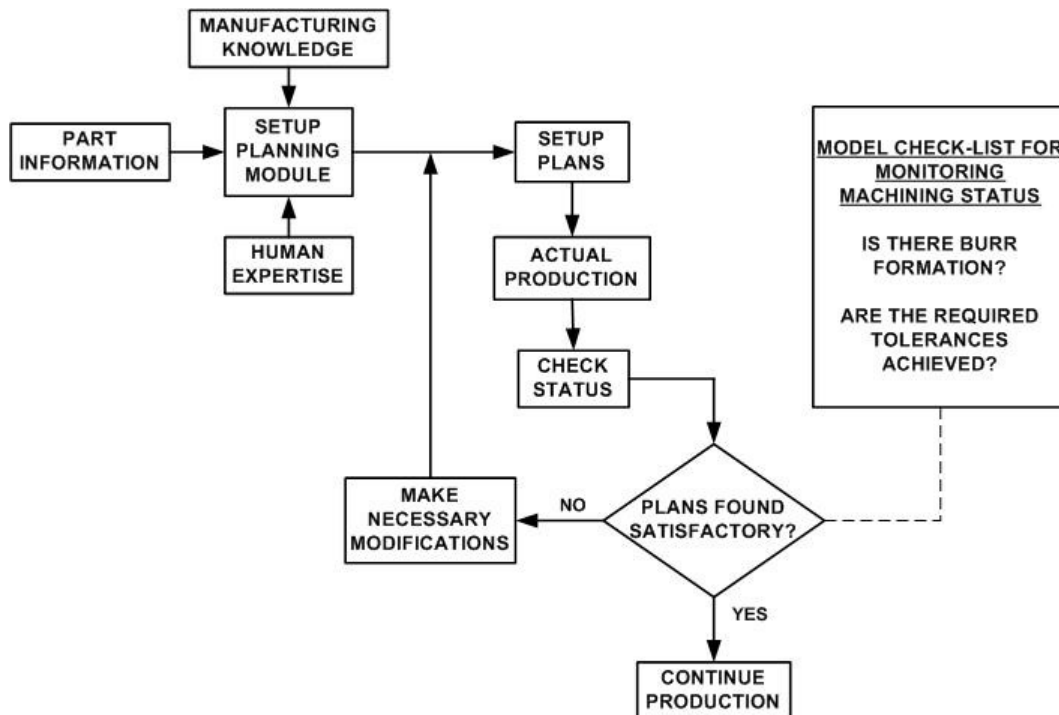
The overall membership grade  $\mu_{o_{datum}}$  is dependent on the most poorly performing criteria for datum selection. The value of  $\mu_{o_{datum}}$  for each candidate face is calculated. The face having maximum value of  $\mu_{o_{datum}}$  will be selected as the primary datum for fulfilling the need for good tolerance relation, good surface area and good surface quality.

Requirements for selecting datum may vary. One requirement may be ‘very good tolerance relation’, ‘good surface area’ and ‘good surface quality’. In such cases, linguistic information can be easily incorporated using fuzzy set quantifiers called hedges. Hedges are the terms that modify the meaning of a fuzzy variable.

Some examples of hedges are *very*, *extremely*, *fair*, *indeed*, *etc.* For example, if a face has membership grade  $\mu_{gt}$  in the set of ‘good tolerance relation’, it can be assigned a membership grade  $\mu_{gt}^2$  in the set of ‘very good tolerance relation’. The fuzzy membership grade for the fuzzy variable good tolerance relation is concentrated using the hedge *very* as,  $\mu_{vgt}^{very} = \mu_{gt}^2$ , where  $\mu_{vgt}$  is the membership grade for very good tolerance relation. After finding ‘ $\min(\mu_{vgt}, \mu_{gsa}, \mu_{gsq})$ ’ for all candidate faces, the face with the maximum membership grade among these minimums is selected as datum. If the requirement is to select very good tolerance relation, good surface area and fair surface quality, the fuzzy membership grade for good surface quality is dilated using the hedge *fair* as,  $\mu_{fsq}^{fair} = \sqrt{\mu_{gsq}}$ , where  $\mu_{fsq}$  is the membership grade for fair surface quality and datum is selected in a similar way as described above.

#### 4.4 Strategy for Adaptive Learning and Updating the Knowledge-base

Traditional softwares for automating setup planning are static in nature and they do not respond to the changes in the situation. Capability of learning from the feedback and adaptability to the actual condition on the shop floor is important for a setup planning system. In this section, a strategy for adaptive learning from the feedback received from actual production stage is described. The proposed approach enables the setup planning system to modify and adapt the knowledge-base to the actual situations on the shop floor. Figure 4.3 shows the flow chart for the feedback system for adaptive learning.



**Figure 4.3.** Flow chart for adaptive learning from shop floor feedback

Checking the status of the actual machining of the parts is essential for feeding real time information to the setup planning system. The proposed setup planning system provides a checklist with the setup plan to monitor certain situations where decision is to be taken based on the shop floor feedback. Monitoring the machining conditions against the checklist is done to confirm the satisfactory performance of the setup plan. The quality control engineer will monitor if burrs are present and if desired tolerances and required surface finish are achieved. If some anomaly is found, the information is fed back to the setup planning system and modifications are made. For example, the ambiguous precedence rule, Face → Drill hole/ Drill hole → Face (as discussed in Section 4.3.1) is considered. For a particular combination of material, tool and feed rate for drilling a hole, Rule 2 (Face → Drill hole) is selected during setup planning stage assuming no burr will be formed. However, during actual drilling, the process is observed against the conditions given in the checklist in the setup plan and found that there is burr of considerable size. This information is to be fed back to the setup planning system so that the necessary modifications can be made to the knowledge-base and the new knowledge is stored.

For certain cases when the overall membership grade  $\mu_c$  for burr formation is neither high nor low (say  $0.45 < \mu_c < 0.55$ ), decision to follow the rule, Face  $\rightarrow$  Drill hole/ Drill hole  $\rightarrow$  Face depends on the feedback from the shop floor. Similarly, actual machining can be monitored in the shop floor in case of other ambiguous cases and feedback can be provided.

The strategy can be implemented as follows. Assume that the value of overall membership grade  $\mu_c$  for burr formation (from Equation 4.15) is  $\mu_1$  (which is low) for a particular combination of material, tool and feed rate indicating no burr will be formed. During actual drilling process, it is found that there is burr formation of considerable size and observed value of membership grade is assigned  $\mu_2$ . Then the new value of  $\mu_c$  in the knowledge-base becomes  $\mu_c = (\mu_1\mu_2)^{1/2}$ . Supposing, the next observed value of membership grade is  $\mu_3$ , then  $\mu_c = (\mu_1\mu_2\mu_3)^{1/3}$ . Individual membership grades for ductility/tool geometry/feed rate can also be modified if the exact cause for burr formation can be identified. Thus the setup planning expert system keeps learning from its experience from the actual shop floor conditions and keeps updating its knowledge-base. It is necessary and important for such experts systems to keep learning and evolving from experience.

#### **4.5 A Methodology for Fine Tuning the Membership Grades Assigned by an Expert**

Design of fuzzy membership functions greatly affects a fuzzy set based inference system. For a fuzzy input or output variable, membership grades are assigned to map numeric data to linguistic fuzzy terms. The knowledge of human experts plays a vital role in assigning these membership grades. Most of the time, different estimates of a fuzzy variable are decided based on expert's opinion. However, there is a need to optimize these estimates to enhance performance.

Different methods have been proposed in the literature for automatic generation of membership grades/membership functions. Some methods eliminate the need for an expert's opinion and knowledge is acquired from training examples. Medasani *et*

*al.* [1998] provided an overview of various techniques used for membership function generation for pattern recognition. The authors are of the view that there is no single best method that can be used for all applications. Choice of a method depends on the problem at hand. Hong and Lee [1996] proposed a methodology for automatic generation of membership functions and fuzzy IF–THEN rules for developing a fuzzy expert system. The output values are grouped based on the similarity between two adjacent data and triangular membership functions are used for both input and output variables. The system learns from a set of given training examples. Chen and Wang [1999] stressed on the fact that the parameter identification *i.e.*, deciding the number of membership functions, centre, width and cross-over slope (value of the parameter at which membership grade is 0.5) is an important step in designing fuzzy logic based systems. The authors proposed a heuristic method based on fuzzy *c*-means clustering algorithm to find the optimal number of clusters. A hybrid learning approach using an adaptive-network-based fuzzy inference system (ANFIS) is used to optimize the parameters for maximizing the system performance. Liu and Pedrycz [2007] proposed an algorithm for building membership functions based on an axiomatic fuzzy set (AFS) theory. Furukawa and Yamakawa [1995] proposed two algorithms for pattern recognition of hand written characters. The algorithms use example based learning strategy. Initially, the pattern samples are classified based on their outlines and a fuzzy neuron is assigned to each class. Membership function of each fuzzy neuron is decided from the example based learning.

The neural networks have been used to generate and optimize membership functions. Yang and Bose [2006] proposed a strategy to generate membership functions for pattern recognition using self-organizing feature map technique based on unsupervised learning. A comparison with histogram method, fuzzy *c*-means clustering method and feed forward neural network method is presented. Choi and Rhee [2009] proposed three different algorithms based on heuristics, histograms and fuzzy *c*-means clustering for generation of interval type-2 fuzzy membership functions for pattern recognition. In interval type-2 fuzzy membership set, for each element of a universal set, a lower and upper membership grades are defined instead of just one membership grade. Medaglia *et al.* [2002] proposed a method for

generation of membership functions based on Bezier curves. An expert can provide membership grades for each point in the domain and a smooth curve can be obtained by minimizing the sum of the squared errors between the fitted membership function and data. Bai and Chen [2008] developed a methodology for the construction of membership functions for lenient-type, strict-type and normal-type grades for students' evaluation. The scores of the students are inferred by fuzzy reasoning based on the constructed membership function.

Evolutionary algorithms have been used for the optimization of membership functions. Arslan and Kaya [2001] used genetic algorithm to optimize the shape of the membership functions where the initial shape and the parameters of the membership functions are predefined. The base lengths of the input and output fuzzy variables are adjusted to find the optimal membership functions. Bagis [2003] proposed an approach for attaining optimum membership functions for a fuzzy logic controller for the operation of spillway gates of reservoirs during floods. Membership functions for the input and output fuzzy variables are first selected based on experience and intuition. Optimal membership functions are obtained with tabu search algorithm that provides a better performance of the controller. Garibaldi and Ifeachor [1999] proposed a fuzzy expert system for umbilical cord acid-base interpretation of newborn infants. Analysis of acid-base balance in the blood of umbilical cord gives essential information on any lack of oxygen during childbirth. Opinions of several expert clinicians are sought to rank different complex cases and these rankings are used to train the fuzzy expert system. For optimization purpose, a hybrid of simulated annealing and simplex method are used.

From the review of literature, it is evident that membership grade/membership function generation has received significant research attention over the years. However, there are limited attempts on developing a strategy that combines the best of an expert's knowledge and available data for a better solution. The experience and knowledge of an expert is valuable for initial estimates of a fuzzy parameter, although expert's knowledge may not be fully accurate. Therefore, a fine tuning strategy may be applied to the initial membership grades for finding the optimal membership grades.

Considering that the knowledge of an expert is available for the initial estimates of a fuzzy parameter, in the present work, a methodology is proposed for fine tuning these estimates to enhance the performance of a fuzzy set based system. The proposed methodology combines the best of an expert's knowledge and available experimental data to predict the membership grades of fuzzy parameters. Criteria considered for the optimal membership grades are the accuracy of solution and minimum violation of expert's opinion. In Section 4.3.1, an example of burr formation in drilling is discussed to explain the strategy for uncertainty management in feature precedence relations. The membership grades of the input fuzzy parameters for burr formation ( $\mu_{\text{duc}}$ ,  $\mu_{\text{tool}}$  and  $\mu_{\text{feedrate}}$  as given in Table 4.1) are decided based on expert's opinion. The proposed methodology is applied for fine tuning these membership grades given by the expert and accurately predicting the burr height in drilling.

#### 4.5.1 Problem definition

There are many situations where the membership grades of two or more fuzzy variables are combined to obtain an overall membership grade. For example, consider that a certain job requires sufficient amount of intellectual ability as well as physical fitness. Now, if a candidate has a membership grade of  $\mu_{\text{in}}$  in the set of 'intellectual' and a membership grade of  $\mu_{\text{ph}}$  in the set of 'physical fitness', then his/her overall membership grade  $\mu_{\text{c}}$  in the set of 'suitable candidates' can be employed using some fuzzy set theoretic operation, such as

$$\mu_{\text{c}} = \min(\mu_{\text{in}}, \mu_{\text{ph}}) \quad (4.17)$$

In general, the overall computed/predicted membership grade  $\mu_{\text{c}}$  of a fuzzy output variable for  $n$  fuzzy input variables can be expressed as

$$\mu_{\text{c}} = f(\mu_1, \mu_2, \dots, \mu_n), \quad (4.18)$$

where  $\mu_i$  ( $i=1$  to  $n$ ) denotes the membership grade corresponding to  $i^{\text{th}}$  fuzzy set and  $f$  is the appropriate fuzzy set theoretic operation. The success of a fuzzy set based method depends on the accurate assignment of membership grades as well as use of an appropriate fuzzy set theoretic operation for obtaining an overall membership grade. The errors in the estimation of these quantities may reinforce or nullify one

another. Hence, it may not be appropriate to apply a fuzzy set based method without the involvement of an expert. However, the estimates of experts may be fine tuned following a systematic mathematical procedure.

In this work, it is assumed that the confidence level in the estimation of  $\mu_c$  is the highest, followed by the confidence in the appropriateness of  $f$ . There may be significant uncertainty in the estimation of  $\mu_i$  ( $i=1$  to  $n$ ) and expert may specify it as a range, rather than a fixed real number. The task is to fine tune the values of  $\mu_i$ s for satisfying Equation (4.18). In doing so, there should not be significant deviation from the opinion of the expert. If this task cannot be completed satisfactorily, then the operator  $f$  has to be modified.

Compared to the fuzzy rule based inference systems, the adopted methodology is much simpler. In fuzzy rule based systems, inference procedure consists of several steps. For example, Mamdani inference process is performed in four steps: fuzzification of the input variables, rule evaluation, aggregation of the rule outputs and defuzzification for a crisp output value. However, in Eq (4.18), the fuzzy input and output variables are related through an appropriate fuzzy set theoretic operator  $f$  and output is obtained in a single step by executing operation  $f$  on the input variables  $\mu_i$  ( $i=1$  to  $n$ ).

#### 4.5.2 Fine Tuning the Membership Grades

The membership grades assigned by the expert can be slightly modified based on the observed data. The difference between the computed/predicted and observed overall membership grades can be minimized in the least square sense. The overall methodology comprises the following steps:

Step 1: Data is generated from experiments/ polling/interviews with experts for the fuzzy output variable for which the overall observed membership grade  $\mu_o$  is to be obtained.

Step 2: Overall observed membership grade  $\mu_o$  is constructed based on the data.

Step 3: Membership grades  $\mu_i$  ( $i=1$  to  $n$ ) for the fuzzy input variables, their variable bounds, and the appropriate fuzzy set theoretic operator  $f$  is selected based on expert's knowledge.

Step 4: Operator  $f$  is applied to  $\mu_i$  ( $i=1$  to  $n$ ) to obtain the value of overall computed membership grade from Equation (4.18) which is denoted by  $\mu_c$ .

Step 5: Objective is to minimize the difference between  $\mu_c$  and  $\mu_o$  so that observed and computed values of overall membership grades are close to each other giving a suitable solution for the membership grades  $\mu_i$  ( $i=1$  to  $n$ ) of the fuzzy input variables.

The optimization problem is given by

$$\text{Minimize error } E = \sum_{i=1}^k (\mu_c - \mu_o)^2, \quad (4.19)$$

subject to constraints and variable bounds. In Equation (4.19),  $k$  is the number of independent observation. The design variables are  $\mu_i$  ( $i=1$  to  $n$ ), *i.e.* the membership grades of individual attributes.

Step 6: For fine tuning the membership grades of fuzzy input variables, the following two criteria are considered; (i) accuracy of the solution and (ii) deviation of expert's opinion. The accuracy of the solution is expressed in the linguistic form and evaluated as explained below.

The initial estimates of membership grades for the fuzzy input variables and their variable bounds are decided by an expert. The overall computed membership grade  $\mu_c$  is calculated and compared with the overall observed membership grade  $\mu_o$ . The root mean square (RMS) error value is calculated as per the following equation:

$$\text{RMS error} = \sqrt{\frac{\sum_{i=1}^k (\mu_c - \mu_o)^2}{k}} \quad (4.20)$$

An accurate solution will have a low value of the RMS error. Table 4.2 shows the RMS errors and their equivalent numerical values. A solution for  $\mu_i$  ( $i=1$  to  $n$ ) is assigned a numerical value for the level of accuracy attained. A solution with very poor/poor level of accuracy is not acceptable.

**Table 4.2.** The quality of solution based on the accuracy

RMS error	Solution quality	Equivalent numerical value
< 0.08	Excellent	10
0.08–0.1	Very good	9
0.1–0.12	Good	8
0.12–0.15	Satisfactory	7
0.15–0.17	Poor	4
>0.17	Very poor	2

**Step 7:** If accuracy of the solution is not excellent, the variable bounds of the  $\mu_i$  ( $i=1$  to  $n$ ) given by the expert are relaxed slightly and a new solution is obtained. For the new solution, each  $\mu_i$  is compared with the variable bound provided by the expert and its deviation from the given bound is calculated. For a  $\mu_i$  if there is no deviation of the variable bound provided by the expert, it is considered the best. Table 4.3 shows the numerical values assigned to a  $\mu_i$  based on the deviation of expert's opinion.

**Table 4.3.** The level of deviations of expert's opinion

Change in variable bound of a $\mu_i$ given by expert	Level of deviation	Equivalent numerical value
No change	Excellent	10
0.02	Very good	9
0.05	Good	8
0.10	Satisfactory	7
0.15	Poor	4
0.20	Very poor	2

**Step 8:** The new solution is also evaluated for accuracy as in Step 6. For an acceptable solution, the minimum level for accuracy as well as deviation of expert's opinion should be satisfactory. A solution with very poor/poor quality either in accuracy criterion or in deviation of expert's opinion criterion is not acceptable.

**Step 9:** Steps 7 and 8 are repeated and the set of acceptable solutions are obtained. Table 4.4 shows the numerical values for deviation of expert's opinion and accuracy for each acceptable solution. In Table 4.4,  $e_{ij}$  ( $i=1$  to  $n$ ,  $j=1$  to  $m$ ) is the numerical value assigned to each  $\mu_i$  for deviation of expert's opinion and  $E_t$  ( $t=1$  to  $m$ ) is the overall quality value calculated for a solution based on deviation of expert's opinion.

$A_t$  ( $t=1$  to  $m$ ) is the numerical value assigned for the level of accuracy attained by each solution.

**Table 4.4.** Evaluation based on accuracy and deviation of expert’s opinion

Acceptable solutions	Numerical value assigned for deviation of expert’s opinion	Overall quality value for a solution ( $E_t = \sum e_{ij}/n$ )	Numerical value for accuracy ( $A_t$ )
	$\mu_1, \mu_2, \mu_3 \dots \dots \mu_n$		
1	$e_{11}, e_{12}, e_{13}, \dots, e_{1n}$	$E_1$	$A_1$
2	$e_{21}, e_{22}, e_{23}, \dots, e_{2n}$	$E_2$	$A_2$
3	$e_{31}, e_{32}, e_{33}, \dots, e_{3n}$	$E_3$	$A_3$
⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮
$m$	$e_{m1}, e_{m2}, e_{m3}, \dots, e_{mn}$	$E_m$	$A_m$

From the set of acceptable solutions, the solution that satisfies both the criteria with highest possible solution quality is selected as the optimal solution. In some cases, there may be more than one optimal solution leading to a Pareto optimal solution. In a set of Pareto optimal solutions, no solution dominates another solution. In other words, there is no solution in the set which is better (worse) than any other solution from the viewpoint of all the objectives [Dixit and Dixit, 2008].

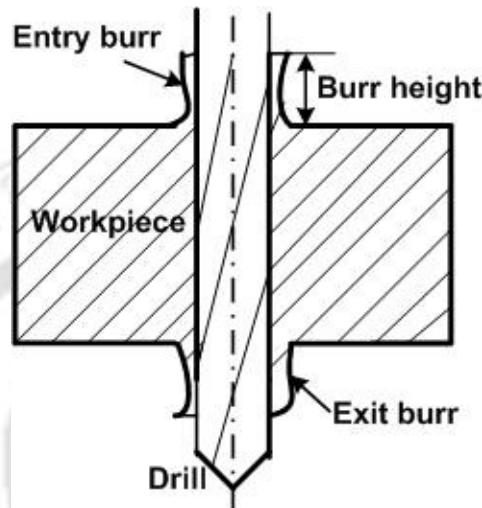
Step 10: If a satisfactory solution cannot be obtained by the above procedure, there may be a need to modify the operator  $f$ .

The proposed method provides a systematic procedure for evaluating all possible solutions and selecting the appropriate one in an interactive manner.

**4.5.3 Application of the Proposed Methodology to Burr Height Estimation**

In this section, the application of the proposed methodology in the estimation of burr height in drilling is described. Burrs are produced during drilling on both entry and exit surfaces of the workpiece due to plastic deformation of the workpiece material. In the present work, heights of entry burrs are measured. The burr height largely depends on the ductility of the material. Figure 4.4 shows the exaggerated view of entry and exit burrs formed during drilling operation. Formation of burrs during drilling is a critical problem which affects surface quality, dimensional

accuracy and safety of handling the product. Burrs are unwanted elements and burr removal involves extra cost. Therefore, significant amount of research has been devoted towards prediction and control of burr formation in drilling.



**Figure 4.4.** An exaggerated view of burr formation in drilling

It is evident from the literature that various parameters affecting burr formation in drilling are material properties, process parameters and drill geometry. Drilling burrs can have different shapes and sizes depending on these parameters. Burr shapes and sizes are observed and classified for different workpiece materials based on experimental studies. Effect of process parameters (feed rate and cutting speed) on burr formation in drilling is widely studied [Stein and Dornfeld, 1997; Min *et al.*, 2001; Pena *et al.*, 2005; Aramendi *et al.*, 2008; Lauderbaugh, 2009]. Feed rate is found to be a significant factor for burr formation in these studies. Burr size is highly affected by the ductility of the workpiece material. More ductile the workpiece material, larger is the burr size. A number of materials with varying ductility are used for experimental studies on burr formation [Stein and Dornfeld, 1997; Min *et al.*, 2001; Pena *et al.*, 2005; Lauderbaugh, 2009; Ko and Lee, 2001]. It is observed that burr height increases with increasing ductility.

Drill geometry has a significant effect on burr shape and size [Min *et al.*, 2001; Lauderbaugh, 2009; Ko and Lee, 2001; Ko *et al.*, 2003]. Optimization of drill geometry can minimize burr size. The main geometrical parameters of a drill that

influence burr size are point angle, chisel edge and corner radius of the cutting edge [Ko and Lee, 2001]. In a later work, a methodology is proposed to minimize burr size in drilling by using step drills instead of conventional drills [Ko *et al.*, 2003]. Burrs formed by a step drill were smaller in size compared to those produced by a conventional drill. For conventional drills, low cutting speeds do not influence burr size [Stein and Dornfeld, 1997]. Effect of cutting speed is not very prominent for burr formation compared to feed rate and ductility of the work material [Min *et al.*, 2001; Lauderbaugh, 2009].

From the review of literature, it is observed that ductility, feed rate and tool geometry are three significant parameters which affect burr formation in drilling. In the present work, burr height is considered as a function of ductility, feed rate and drill geometry. Effect of cutting speed on burr formation is not considered in this study.

#### 4.5.3.1 Experimental Work

A radial drilling machine (Batliboi Limited, BR618 model) is used for drilling holes in the workpiece in the present work. Three different materials of varying ductility, *viz.* aluminium, mild steel and cast iron are used as workpiece material. Workpiece is a circular block of diameter 25 mm and height 30 mm. A two flute high-speed steel drill with 10 mm diameter ( $118^\circ$  point angle and  $30^\circ$  helix angle) has been used for drilling blind holes of depth 15 mm at different feed rates. For each drilling operation, three replicate experiments were performed in the range of feed rate 104–288 mm/min. Spindle speed and cutting velocity are 800 rpm and 25 m/min respectively. The burr height is measured with an Optical Microscope (Axiotech<sup>vario</sup> 100 HD, make: Carl Zeiss) of magnification range 5X to 200X and supported with KS-300 software. Figure 4.5 shows the photographs of the different equipment used for the experimental work. Tables 4.5–4.7 show the maximum burr heights for aluminium, mild steel and cast iron work pieces for four different feed rates respectively.



Radial drilling machine



Optical microscope

**Figure 4.5.** Machine and equipment used for the experiments

**Table 4.5.** Burr heights for different feed rates in drilling aluminium workpiece

Feed rate mm/min	Maximum burr height (mm)		
	Replicate 1	Replicate 2	Replicate 3
104	0.20	0.18	0.16
144	0.24	0.24	0.23
200	0.36	0.34	0.33
288	0.40	0.38	0.37

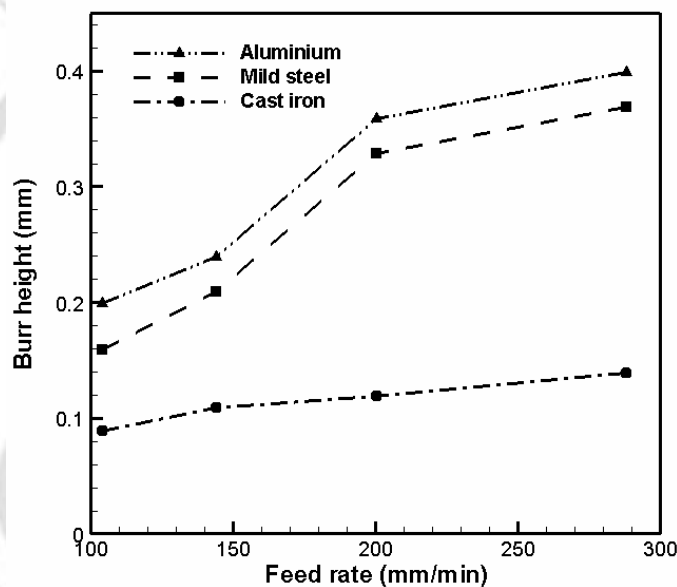
**Table 4.6.** Burr heights for different feed rates in drilling mild steel workpiece

Feed rate mm/min	Maximum burr height (mm)		
	Replicate 1	Replicate 2	Replicate 3
104	0.12	0.16	0.12
144	0.21	0.20	0.21
200	0.33	0.29	0.32
288	0.37	0.32	0.35

**Table 4.7.** Burr heights for different feed rates in drilling cast iron workpiece

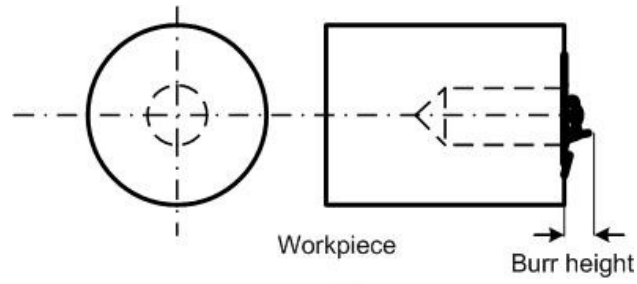
Feed rate mm/min	Maximum burr height (mm)		
	Replicate 1	Replicate 2	Replicate 3
104	0.05	0.09	0.09
144	0.10	0.10	0.11
200	0.12	0.09	0.09
288	0.13	0.14	0.12

Figure 4.6 shows the maximum value of the burr heights in drilling aluminium, mild steel and cast iron work-pieces with different feed rates. It is evident from Figure 4.6 that at the same cutting condition, the burr height is the maximum for aluminium which is a ductile material. For mild steel, burr height is lower than aluminium as mild steel is less ductile than aluminium. For both aluminium and mild steel, there is significant increase in burr height with increase in feed rate. Burr height is very small for cast iron which is a brittle material. Variation of burr height with feed rate is not significant in case of cast iron.

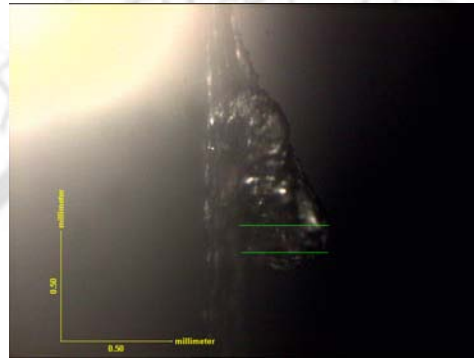


**Figure 4.6.** Burr height with different feed rate

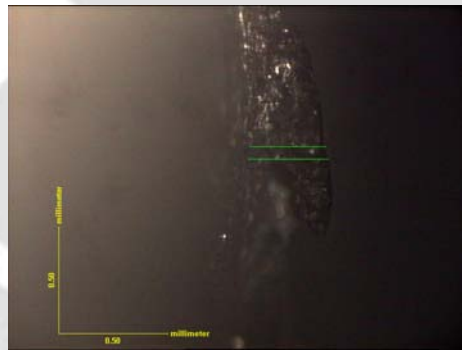
From the experimental study, the maximum and minimum values of burr heights are found as 0.40 mm (aluminium workpiece at 288 mm/min feed rate) and 0.05 mm (cast iron workpiece at 104 mm/min feed rate). Moreover, it is observed that for the replicate experiments, the burr height is varying to some extent. This is due to the inherent statistical variation in the machining process. In case of aluminium and cast iron, the maximum variation of burr heights for replicate experiments is found as 0.04 mm. The maximum variation of burr height for replicate experiments for mild steel is 0.05 mm. Figure 4.7 shows the schematic diagram of the workpiece and burr height and Figure 4.8 shows the maximum value of burr height for aluminium, mild steel and cast iron at feed rate 288 mm/min.



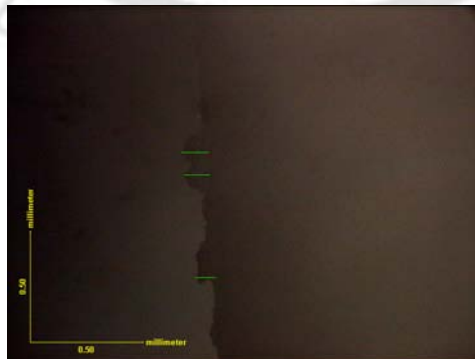
**Figure 4.7.** Workpiece and burr height



(a)



(b)



(c)

**Figure 4.8.** Maximum burr height for (a) aluminium (b) mild steel and (c) cast iron at feed rate 288 mm/min

#### 4.5.3.2 Application of the Proposed Methodology

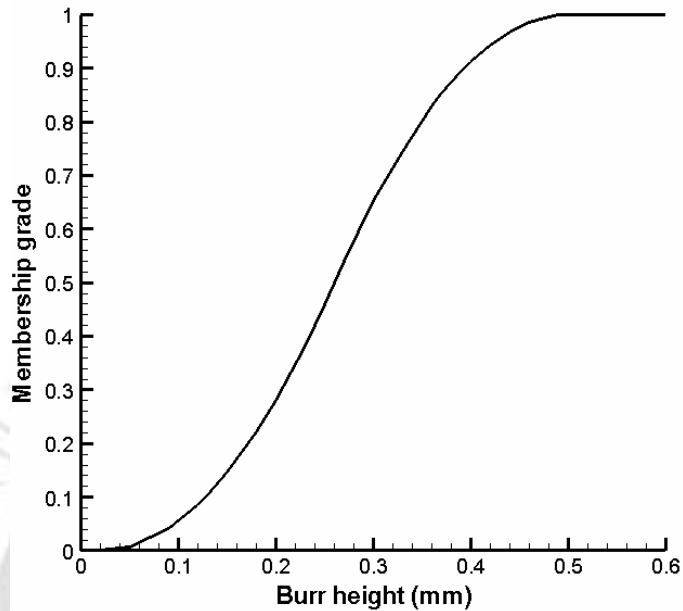
In this section, the proposed methodology is applied in estimation of entry burr height in drilling. To represent different membership grades for burr heights (data obtained from the experiments), the standard  $S$ -function is selected. Equation (4.21) represents the standard  $S$ -function [Zadeh, 1976].

$$S(\mu_o; a, b, c) = \begin{cases} 0 & \text{if } \mu_o \leq a \\ 2 \left( \frac{\mu_o - a}{c - a} \right)^2 & \text{if } a < \mu_o \leq b \\ 1 - 2 \left( \frac{\mu_o - c}{c - a} \right)^2 & \text{if } b < \mu_o \leq c \\ 1 & \text{if } \mu_o > c \end{cases} \quad (4.21)$$

where  $b = \frac{a+c}{2}$ .

In Equation (4.21),  $\mu_o$  represents overall membership grade for observed burr heights and  $a$ ,  $b$ , and  $c$  are the values of burr heights at membership grades 0, 0.5 and 1 respectively. The maximum and minimum values of burr heights are found as 0.40 mm and 0.05 mm from experiments. Based on these values, parameter  $a$  (value of burr height at membership grade 0) is taken as 0.02 mm below which burr height is considered negligible. Parameter  $c$  (the value of burr height at membership grade 1) is taken as 0.5 mm and parameter  $b$  (the value of burr height at membership grade 0.5) is obtained as 0.26 mm.

Figure 4.9 shows the overall membership grades  $\mu_o$  for the observed burr heights. The value of  $\mu_o$  for the maximum burr height 0.40 mm is 0.913 and that for minimum burr height 0.05 mm is 0.008. For aluminium, the maximum variation of burr height for replicate experiments is 0.04 mm (at 104 mm/min feed rate) for which the variation in the value of  $\mu_o$  is 0.11. Thus, there may be an error of the order of 0.11 in the estimation of  $\mu_o$  for aluminium. For mild steel and cast iron, the maximum variations of burr height for replicate experiments are 0.05 mm (at 288 mm/min feed rate) and 0.04 mm (at 104 mm/min feed rate) and errors in the value of  $\mu_o$  for mild steel and cast iron may be 0.13 and 0.04 respectively.



**Figure 4.9.** Membership function for observed burr heights

From the knowledge acquired from the literature, it is observed that ductility of the workpiece material, feed rate and tool geometry are the three significant parameters that affect burr formation in drilling. As discussed in Section 4.3.1, the varying effect of these input parameters on burr height is considered by adopting the relation given by Equation (4.15). The ductility of the workpiece material plays a dominant role compared to the other two parameters. The overall computed membership grade  $\mu_c$  for burr height is calculated from Equation (4.15). The initial values of the  $\mu_i$  ( $\mu_{duc}$ ,  $\mu_{feedrate}$  and  $\mu_{tool}$ ) and their variable bounds are provided by the expert. For three different materials of varying ductility and three different feed rates, the values are given in Table 4.8. In the experimental work, a conventional drill with  $118^\circ$  point angle is used for drilling operation. For conventional drills, burr height is found more [Ko *et al.* 2003]. Therefore tool geometry ( $\mu_{tool}$ ) is assigned the membership grade 0.9 in Table 4.8.

**Table 4.8.** Input parameter membership grades and variable bounds given by the expert

Workpiece material	$\mu_{duc}$		Variable bound	Feed rate (mm/min)	$\mu_{feedrate}$		Variable bound	$\mu_{tool}$	Variable bound
	$\mu_{duc1}$	$\mu_{duc2}$			$\mu_{feedrate1}$	$\mu_{feedrate2}$			
Aluminium	$\mu_{duc1}$	0.9	0.75–0.95	288	$\mu_{feedrate1}$	0.8	0.75–0.90	0.9	0.8–1
Mild steel	$\mu_{duc2}$	0.7	0.60–0.75	200	$\mu_{feedrate2}$	0.5	0.45–0.60		
Cast iron	$\mu_{duc3}$	0.2	0.15–0.25	104	$\mu_{feedrate3}$	0.3	0.15–0.30		

The overall membership grade  $\mu_c$  for burr height is calculated from Equation (4.15) for all the combinations of workpiece material, feed rate and tool geometry. The objective function given by Equation (4.19) is minimized using optimization technique FMINCON in MATLAB (Version 7). FMINCON attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. The design variables are the membership grades of individual attributes, *i.e.*  $\mu_{duc1}$ ,  $\mu_{duc2}$ ,  $\mu_{duc3}$ ,  $\mu_{feedrate1}$ ,  $\mu_{feedrate2}$ ,  $\mu_{feedrate3}$  and  $\mu_{tool}$ . Following the methodology described in Section 4.5.2, each solution is evaluated for accuracy and deviation of expert's opinion. Table 4.9 shows the acceptable solutions satisfying the criteria that the minimum level for accuracy as well as deviation of expert's opinion should be satisfactory. Between Solutions 1 and 2, Solution 1 is better. Among the Solutions 3–7, Solution 3 is the best as it dominates the other solutions. However, between Solutions 1 and 3, no solution dominates the other. Both the solutions form a set of Pareto optimal solution from the viewpoint of satisfying the criteria for accuracy and deviation of expert's opinion. A higher level of decision is required to choose between these two solutions. Table 4.10 shows the values of design variables for Solution 1 and 3.

**Table 4.9.** Acceptable solutions based on accuracy and deviation of expert’s opinion

Solution	Overall quality value for a solution for deviation of expert’s opinion ( $E_t$ )	Numerical value assigned for accuracy ( $A_t$ )
<b>1</b>	<b>9.43</b>	<b>7</b>
2	8.57	7
<b>3</b>	<b>8</b>	<b>8</b>
4	7.86	8
5	7.71	8
6	7.43	8
7	7.14	8

**Table 4.10.** The optimal solutions for the membership grades of input parameters

Input parameter $\mu_i$	Solution-1	Solution-3
$\mu_{duc1}$	0.95	0.99
$\mu_{duc2}$	0.80	0.80
$\mu_{duc3}$	0.10	0.10
$\mu_{feedrate1}$	0.90	0.95
$\mu_{feedrate2}$	0.60	0.70
$\mu_{feedrate3}$	0.15	0.05
$\mu_{tool}$	0.86	0.81

For validation of the proposed method, drilling experiments were performed at an intermediate feed rate of 144 mm/min. The maximum burr heights of three replicate experiments for aluminium at feed rate 144 mm/min were found as 0.24 mm, 0.24 mm and 0.23 mm. Corresponding overall membership grade  $\mu_o$  of these observed burr heights are 0.42, 0.42 and 0.38. The predicted membership grade  $\mu_c$  is 0.54 with the initial expert’s values of  $\mu_i$  ( $i=1$  to  $n$ ) which gives a difference of 0.12, 0.12 and 0.16 with the observed  $\mu_o$  values of the three replicate experiments respectively. However, the value of  $\mu_c$  is 0.43 with the fine tuned values of  $\mu_i$

(Solution-3 in Table 4.10) giving a difference of 0.01, 0.01 and 0.05 with the observed  $\mu_o$  values of the replicate experiments. Thus, there is a better matching of  $\mu_c$  and  $\mu_o$  values with fine tuned values of  $\mu_i$  than with initial expert's values of  $\mu_i$ . For mild steel, the burr heights of three replicate experiments were found as 0.21 mm, 0.20 mm and 0.21 mm with corresponding values of  $\mu_o$  as 0.31, 0.28 and 0.31. The value of  $\mu_c$  (0.42) with the initial expert's values of  $\mu_i$  gives a difference of 0.11, 0.14 and 0.11 with observed  $\mu_o$  values whereas the value of  $\mu_c$  (0.34) with fine tuned values of  $\mu_i$  gives a difference of 0.03, 0.06 and 0.03. For cast iron, the burr heights of three replicate experiments were found as 0.10 mm, 0.10 mm and 0.11 mm with corresponding values of  $\mu_o$  as 0.06, 0.06 and 0.07. The value of  $\mu_c$  (0.12) with the initial expert's values of  $\mu_i$  gives a difference of 0.06, 0.06 and 0.05 with observed  $\mu_o$  values whereas the value of  $\mu_c$  (0.04) with fine tuned values of  $\mu_i$  gives a difference of 0.02, 0.02 and 0.03.

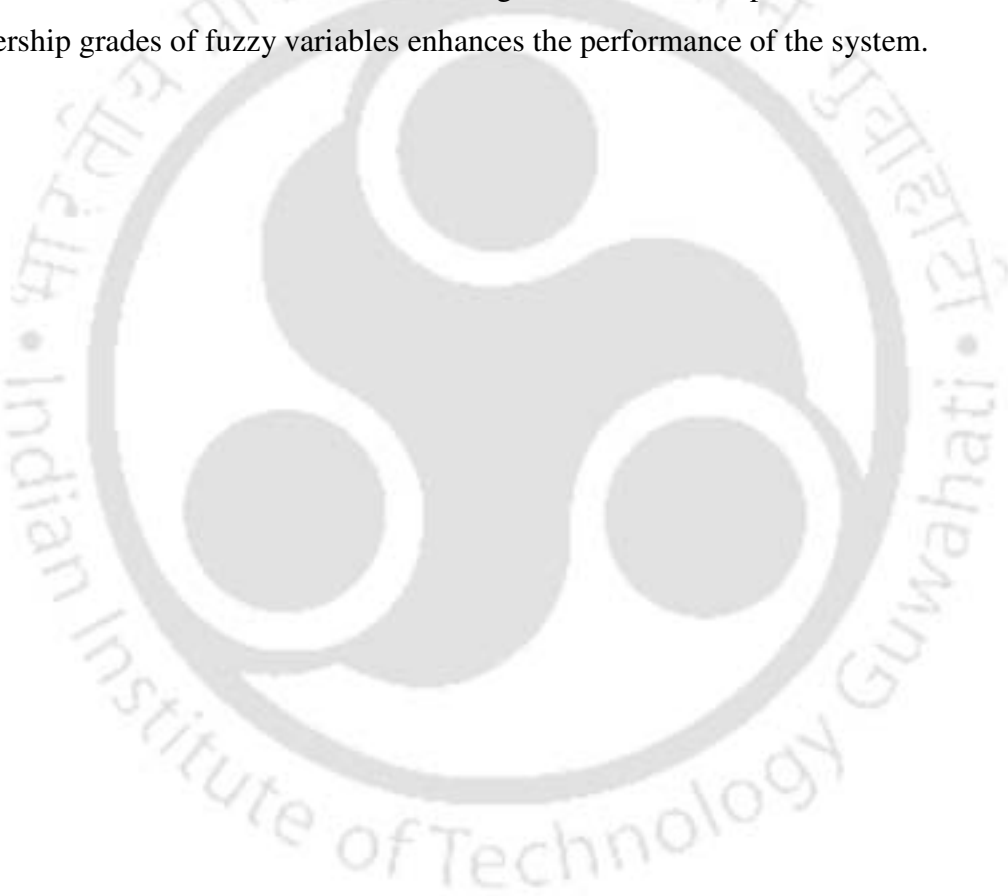
Thus it is observed that in all the three cases, the fine tuned values of  $\mu_i$  ( $i=1$  to  $n$ ) give better matching of  $\mu_c$  and  $\mu_o$  than with the initial expert's values of  $\mu_i$ . Fine tuning of the initial expert's estimates has enhanced the performance of the burr height prediction methodology. The methodology is suitable where limited information is available initially and information value keeps on increasing. The proposed methodology provides a systematic procedure for evaluating all possible solutions and selecting the appropriate one in an interactive manner.

#### **4.6 Summary**

In this chapter, an overview of fuzzy set based methodology for updating the knowledge-base of the expert system is presented. Brief background knowledge on fuzzy set theory is presented describing its essential elements. As setup planning has to be carried out in an environment of uncertainty particularly in feature precedence relations and datum selection, fuzzy set theory is used to deal with uncertainties. The strategy for uncertainty management is explained with different examples. Moreover, the proposed setup planning system has the capability for modifying and adapting itself to the changes based on the shop floor data. It provides a checklist

with the setup information to be used in the shop floor for providing the appropriate feedback. The feedback is used for modifying the setup plan appropriately.

Next, a methodology for fine tuning the initial membership grades assigned by experts for fuzzy variables is discussed in detail. The proposed methodology combines the best of an expert's opinion and experimental data for fine tuning the membership grades. The methodology is applied to the estimation of burr height in drilling holes in different materials. Data on burr height is collected from experiments. It is observed that fine tuning of the initial expert's estimates of membership grades of fuzzy variables enhances the performance of the system.



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## **An Experimental Study on the Effect of Datum Surface Roughness on Parallelism and Perpendicularity Tolerances**

### **5.1 Introduction**

In setup planning, selection of proper datum is essential for attaining the specified tolerances of the machined component. At present, manufacturing industry is faced with the challenges of product variety and customization combined with the requirement of enhanced product quality at lower cost. Attaining the specified design tolerances is a key factor for the quality as well as the functionality of a component. It is the task of process planning to select appropriate processes and machines to ensure that design tolerance requirements are met. While machining a component, the different features of the component are assigned to different setups based on several criteria such as tool approach direction (TAD) of the feature, tolerance requirements, precedence relations, feature geometry, and feature interactions. Selection of proper datum for machining the features in a setup is a crucial task. Setup datum provides a definite and fixed position for machining the component. Selection of datum as well as its surface quality is very important for tolerance requirements of the features comprising the part. Geometrical tolerances such as parallelism, perpendicularity, angularity, and position need datum references. Some dimensional tolerances such as the distance between two parallel surfaces also need datum references. Therefore, the study of datum surface quality needs considerable attention.

Selection of the proper datum is one of the most challenging tasks that has received some research attention over the years. The approaches found in the literature for selection of datum are diversified in terms of criteria considered, such as total area of a face, its orientation, tolerance relation with other features, and symmetry and intricacy of the face. Large and maximum area face has been the most

widely used criterion for selecting the primary datum for machining [Gologlu, 2004; Senthil Kumar *et al.*, 1992]. However, surface area is not the only consideration for selecting datum. For proper location, the surface quality of datum is also important. Usually, the datum surfaces are the machined surfaces [Gologlu, 2004; Roy and Sun, 1994; Senthil Kumar *et al.*, 1992].

Many researchers consider tolerance relations among features as the prime criteria for selecting datum. Mei *et al.* [1995] proposed an artificial neural network based methodology for automatically selecting datums for rotational parts. The input to the neural network consists of the geometry of the part, and the tolerance specifications among the different part surfaces. The output of the network gives the datum surfaces selected for locating and clamping. The methodology proposed by Huang and Xu [2003] first considers critical tolerance relations among surfaces and then the area of a surface for datum selection for machining prismatic parts. To attain tight tolerance relationships, features should preferably be machined in the same setup using the same datum. Considering it, Guo *et al.* [2009] proposed a five-axis machining method for prismatic parts where features with different tool approach directions can be machined in the same setup with the same datum leading to better tolerance achievement. The authors performed optimization of operation sequences and setup determination using particle swarm optimization method.

A number of sources of manufacturing error are datum related such as locating error, clamping error, datum feature (surface) error, *etc* [Huang *et al.* 2004]. In a multi-station machining process, as the locating datums are changed for each station, machining errors get accumulated. Djurdjanovic and Ni [2003] modelled the influence of these errors on dimensional errors of a component for a multi-station machining process. Qin *et al.* [2007] proposed a model for prediction of workpiece machining error that considers workpiece position error, the workpiece elastic deformations and the inconsistent datum error.

It is well recognized that surface finish is one of the criteria for assessing the suitability of a face to be selected as locating datum [Hebbal and Mehta, 2008; Kim *et al.* 1996]. Ong and Nee [1998] proposed a fuzzy set based evaluation procedure to

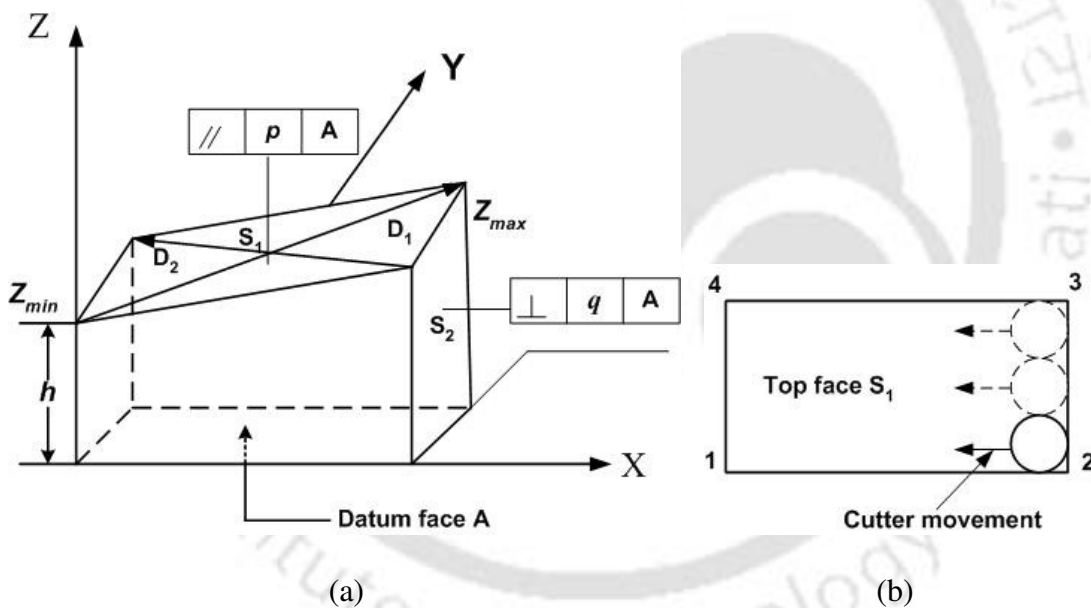
assess the suitability of the features of a part to be used as fixturing features for machining of other features of the part. Surface finish of a feature is one of the criteria considered in addition to surface area, orientation, symmetry and intricacy. Some researchers carried out theoretical and experimental studies on the effect of surface roughness of workpiece and datum on workpiece location and workpiece-fixture contact condition. Lee *et al.* [2001] studied the effect of surface roughness of the workpiece and datum on locating precision in multi-station machining process. They found that the level of alignment precision decreases with increase in surface roughness. Deiab and Elbestawi [2005] presented the results of an experimental investigation on the tribological condition of workpiece-fixture contact surface considering surface roughness of the workpiece, fixture element, normal load, and workpiece material. It was observed that the friction coefficient decreases as the normal load increases.

However, the issue of effect of datum surface roughness on the geometrical tolerances of a component has not been well addressed. In the literature, not much work is available that relates the effect of datum surface roughness to the geometrical tolerances of a component. Although it is believed that a machined surface is to be used as a datum for machining, the appropriate range of surface roughness to achieve a particular tolerance level is not available in open literature. However, the importance of selection of proper datum for tolerance requirements of the features in a setup can not be overlooked. In view of it, an experimental study is conducted to investigate the effect of datum surface roughness on two geometric tolerances, *viz.* parallelism and perpendicularity in machining of prismatic components. A simplified model is proposed for interpreting the experimental results. The knowledge obtained from the experimental results is incorporated in the knowledge-base of the setup planning expert system (described in Chapter 3) in the form of rules. The knowledge can be updated based on the shop floor feedback using the adaptive learning strategy discussed in Section 4.4, Chapter 4.

In this paragraph, a brief definition of parallelism and perpendicularity tolerances are presented. Parallelism specifies that all points on a given surface, axis, line or centre plane must be equidistant from a datum. Parallelism tolerance is the

maximum allowed deviation of parallelism from the true position. It requires a datum reference and may be defined between two planes, a plane and a line/axis or two lines/axes. A parallelism tolerance zone is formed by two hypothetical parallel planes/lines/axes and they are spaced apart by a distance equal to the parallelism tolerance. The tolerated feature should lie within this zone. Perpendicularity is the condition of a surface or an axis being at a right angle to a datum plane or axis. Perpendicularity tolerance is the maximum allowed deviation of the two features from right angle and it requires a datum reference.

## 5.2 Experimental Procedure



**Figure 5.1.** (a) Workpiece with the tolerances (b) Cutter traverse direction

Figure 5.1 (a) shows a workpiece where the top face  $S_1$  has a parallelism tolerance  $p$  and the vertical face  $S_2$  has a perpendicularity tolerance  $q$  with respect to the datum face  $A$ . In this work, same datum face  $A$  is used for measuring parallelism and perpendicularity. Figure 5.1 (b) shows the traverse direction of the end mill cutter for machining the top face  $S_1$ . The table feed is along the longest dimension of

the workpiece. The machining is completed after three longitudinal traverses of the workpiece as shown in Figure 5.1 (b). The experiments were carried out on a vertical milling machine and a universal milling machine using cast iron and perspex work materials for different centre-line average (CLA) values of datum surface roughness in the range of 1.5–6.35  $\mu\text{m}$ . The dimensions of the cast iron and perspex work pieces are 84×46×50  $\text{mm}^3$  and 100×50×12  $\text{mm}^3$ , where 50 mm and 12 mm are the heights of the work pieces respectively. The milling machines provide different speeds ranging from 45 rpm to 2000 rpm and feed ranging from 16 mm/min to 800 mm/min. The tool used was 20 mm diameter end mill (make: Widia) with two carbide inserts with a tip radius of 0.8 mm. The workpiece datum face A was machined in the vertical milling machine by varying the process parameters to obtain different values of datum roughness. For measuring the CLA surface roughness values ( $R_a$ ) of datum surface, Pocket Surf (Mahr, GMBH) having a measuring range of 0.03–6.35  $\mu\text{m}$  was used. With the datum face A at different roughness each, the top face  $S_1$  was machined in the vertical milling machine at 90 rpm cutting speed, 40 mm/min feed and at two different depths of cut, 0.2 mm and 0.4 mm respectively. The vertical component of the resultant cutting force during machining of the top face for each case of datum roughness was measured with a piezo-electric Kistler 9272 dynamometer. Signals from the dynamometer were amplified through charge amplifier of B&K 5015 model. The workpiece was placed on a Carl Zeiss make Coordinate Measuring Machine (CMM, Vista 1620) and the Z coordinate values of different points on the top face  $S_1$  along the two diagonals  $D_1$  and  $D_2$  (Figure 5.1 (a)) were measured for each datum roughness case. Z coordinate values of the points on the top face give an idea about parallelism tolerance. A ball type mechanical touch probe TP2 was used to measure the Z coordinates in the CMM. Calibration of the probe was done prior to the measurements to compensate for the probe stylus radius and variations in the stylus pre-travel. Effective probe stylus diameter was 3.287 mm. For each diagonal, a set of sample points were probed on the top face  $S_1$ . The point with the minimum Z coordinate value  $Z_{min}$ , on the top face  $S_1$  was taken as the base point and the absolute differences in Z coordinate values of other points with respect to this base point were calculated and

plotted against the measured sample points. Flatness of the datum face was also measured in the CMM for each case.

Similarly, to study the effect of datum surface roughness on perpendicularity, the vertical face  $S_2$  of the workpiece was machined in the vertical milling machine in the same position as shown in Figure 5.1 (a). With the datum face A at different roughness each, the face  $S_2$  was machined at 90 rpm cutting speed, 40 mm/min feed and 0.2 mm depth of cut. A four flute high-speed steel end mill with 16 mm diameter and  $30^\circ$  helix angle was used for machining face  $S_2$ . Perpendicularity was measured in the CMM using the facility for measuring perpendicularity tolerance between two planes. Figure 5.2 shows the photographs of the different machines and equipment used for the experimental work.

### 5.3 Observations

This section presents the observations and the statistical analysis of the experimental results on the study of the effect of datum surface roughness on parallelism and perpendicularity.

#### 5.3.1 Observations on Parallelism

Figure 5.3 shows the variations of difference in Z coordinate values of the points along diagonals  $D_1$  and  $D_2$  of the machined top face  $S_1$  with respect to the  $Z_{min}$  value for the sample points for experiments done in the vertical milling machine for cast iron workpiece. The variation in Z coordinate along a diagonal gives the indication of parallelism error in that direction. The experiments were conducted for datum roughness values  $R_a$  of 1.74  $\mu\text{m}$ , 2.14  $\mu\text{m}$ , 3.29  $\mu\text{m}$ , 3.90  $\mu\text{m}$ , 4.86  $\mu\text{m}$ , 5.43  $\mu\text{m}$  and 6.35  $\mu\text{m}$ . The corresponding top face roughness values were obtained as 2.33  $\mu\text{m}$ , 2.30  $\mu\text{m}$ , 2.32  $\mu\text{m}$ , 2.28  $\mu\text{m}$ , 2.33  $\mu\text{m}$ , 2.32  $\mu\text{m}$  and 2.29  $\mu\text{m}$ , indicating that there is no significant change in the top face roughness with change in the datum roughness. From Figure 5.3, it can be observed that Z coordinates vary non-linearly along the diagonals owing to flatness error. The differences in the Z coordinate values of the points along the diagonals increase with increase in datum roughness from 1.74  $\mu\text{m}$  to 3.90  $\mu\text{m}$ . This is expected as a rough datum provides poor location of workpiece



Vertical milling machine



Coordinate measuring machine



Universal testing machine



Charge amplifier

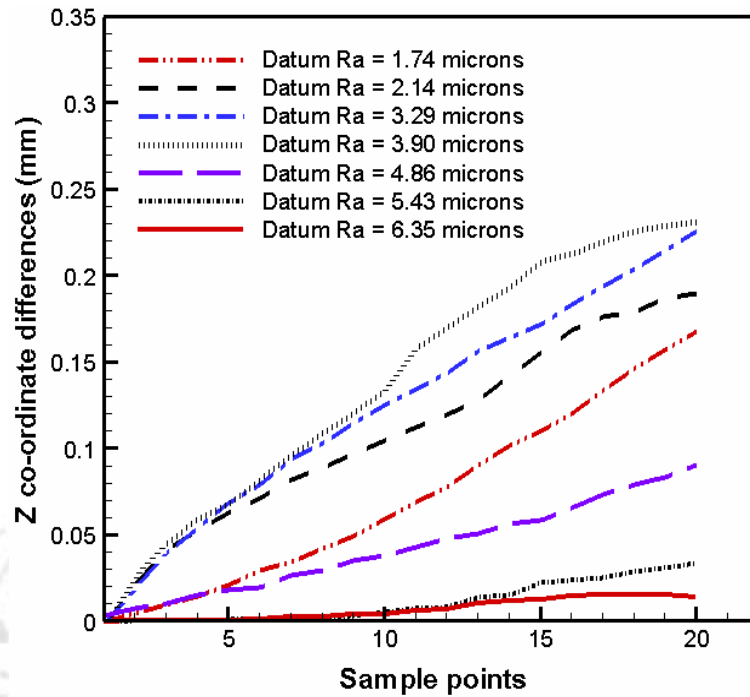


4-component dynamometer

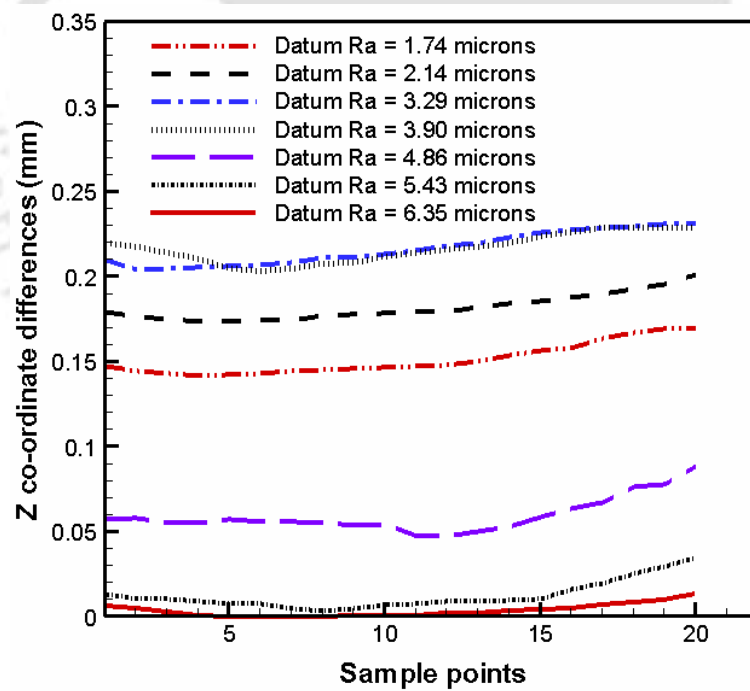


Surface roughness measuring instrument

**Figure 5.2.** Machines and equipment used for the experiments



(a)



(b)

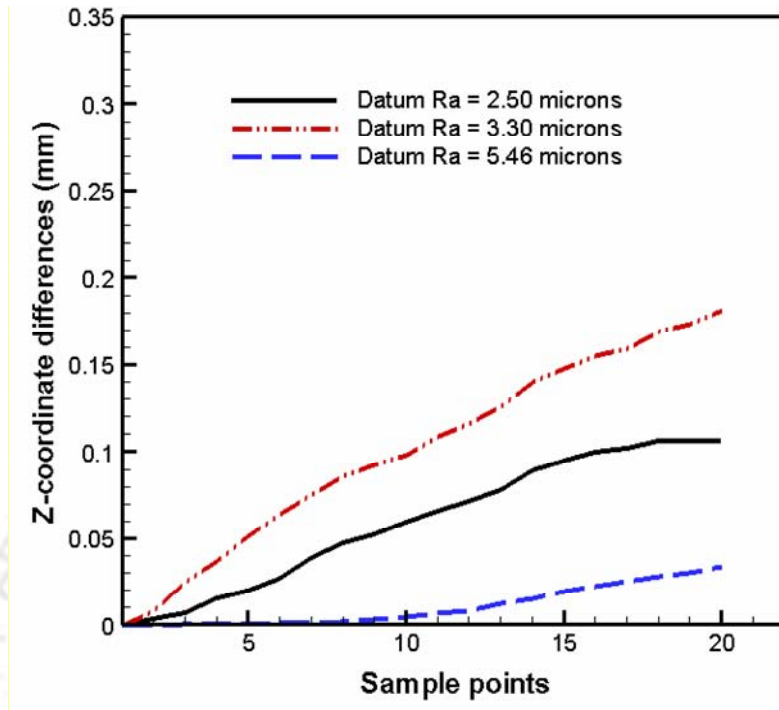
**Figure 5.3.** Variation of Z coordinate differences with sample points for machining of cast iron workpiece on vertical milling machine (a) along  $D_1$  (b) along  $D_2$

on the machine bed. However, as the datum roughness becomes higher ( $R_a = 4.86 \mu\text{m}$ ), the differences in the  $Z$  coordinate values reduce significantly. Further increase in datum roughness to  $R_a$  of  $5.43 \mu\text{m}$  and  $6.35 \mu\text{m}$  shows that the differences in the  $Z$  coordinate values decrease with increasing surface roughness. Parallelism tolerance is the least for the highest datum roughness case with  $R_a$  of  $6.35 \mu\text{m}$ . An intermediate datum roughness value ( $R_a = 3.90 \mu\text{m}$ ) gives the worst value of parallelism tolerance amongst the cases studied.

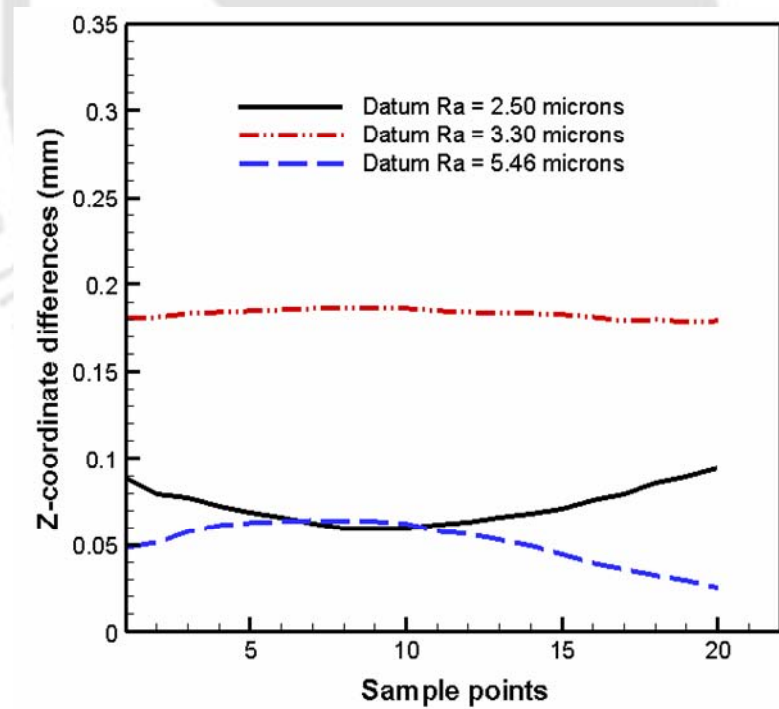
The experimental results reveal that a smooth datum ( $R_a = 1.74 \mu\text{m}$ ) provides fair parallelism tolerance and then, with increase in datum roughness upto  $R_a$  of  $3.90 \mu\text{m}$ , parallelism tolerance keeps on increasing. On further increase of datum roughness, parallelism tolerances reduce to values lower than that obtained with the smooth datum. The trends along diagonals  $D_1$  and  $D_2$  are different in all the cases.

As the cutter cuts from point 2 to point 1 (Figure 5.1 (b)), owing to inherent accuracy limitation of table movement, more material is removed at point 1 than at point 2, making point 1 as the lowest point on the machined surface. Further, as the milling is done in three traverses, due to the combined error of the table motion and cross-slide movement, the generated machined surface is inclined along the width direction (with line 1-2 at a lower level compared to line 3-4). Thus, point 3 is at sufficiently higher level compared to point 1. In all the cases, the difference between  $Z$  coordinates of point 1 and point 3 is more compared to difference between  $Z$  coordinates of point 2 and point 4, which is due to the inherent error of the milling machine.

Figure 5.4 shows the results of a set of experiments done on the universal milling machine where the datum surface roughness values were  $5.46 \mu\text{m}$ ,  $3.30 \mu\text{m}$  and  $2.50 \mu\text{m}$  respectively. Top face roughness values were obtained as  $3.25 \mu\text{m}$ ,  $3.32 \mu\text{m}$  and  $3.48 \mu\text{m}$  respectively. The trend of  $Z$  coordinate variation is similar to Figure 5.3. Differences in the  $Z$  coordinate values are less in case of datum with high roughness of  $5.46 \mu\text{m}$  compared to a datum with low roughness values of  $3.30 \mu\text{m}$  and  $2.50 \mu\text{m}$ , thus supporting the observations from Figure 5.3.



(a)



(b)

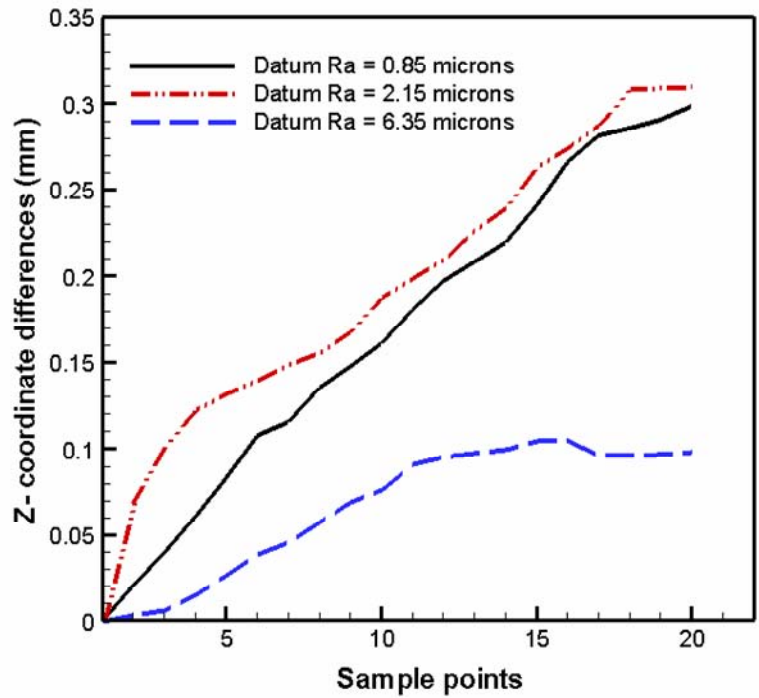
**Figure 5.4.** Variation of Z coordinate differences with sample points for machining of cast iron workpiece on universal milling machine (a) along  $D_1$  (b) along  $D_2$

Figure 5.5 shows the results of a set of experiments done on a perspex workpiece in the vertical milling machine. It resembles the results of the experiments on cast iron. Here the datum surface roughness values were 6.35  $\mu\text{m}$ , 2.15  $\mu\text{m}$  and 0.85  $\mu\text{m}$  respectively and the corresponding top face roughness values were 0.86  $\mu\text{m}$ , 0.87  $\mu\text{m}$  and 0.86  $\mu\text{m}$ . Here too, differences in the Z coordinate values are less in case of datum with high roughness of 6.35  $\mu\text{m}$  compared to datum with low roughness values of 2.15  $\mu\text{m}$  and 0.85  $\mu\text{m}$ . Maximum Z coordinate values were higher compared to cast iron as the workpiece length is more in this case.

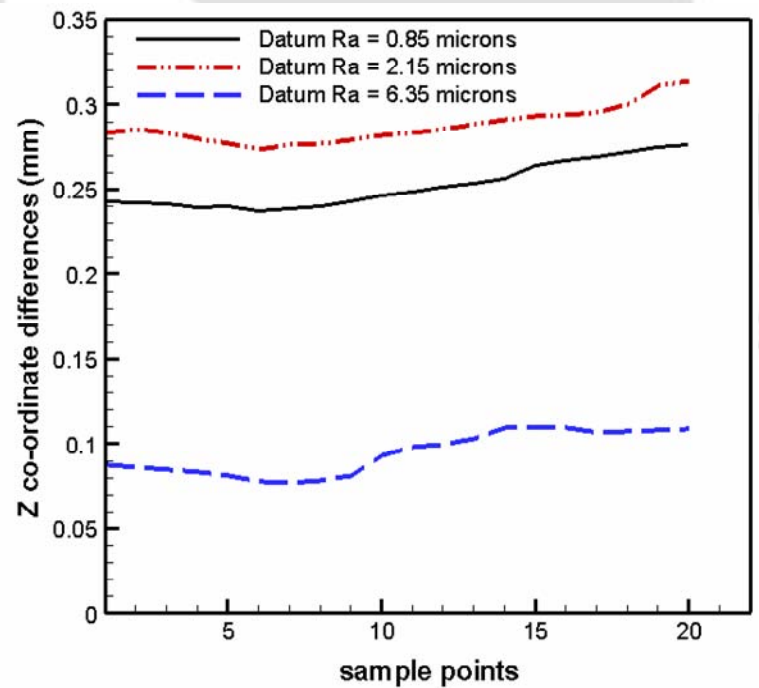
In all the above mentioned cases, the flatness of the datum face ranged between 0.5–0.7  $\mu\text{m}$ . Thus, only the datum surface roughness is the influencing factor in the experiments. In all the cases, the datum with the highest surface roughness of 6.35  $\mu\text{m}$  provided the least parallelism tolerance.

### 5.3.2 Observations on Perpendicularity

The face  $S_2$  (perpendicular to the datum surface A) of the cast iron workpiece was machined for datum roughness values  $R_a$  of 1.74  $\mu\text{m}$ , 2.14  $\mu\text{m}$ , 3.29  $\mu\text{m}$ , 3.90  $\mu\text{m}$ , 4.86  $\mu\text{m}$ , 5.43  $\mu\text{m}$  and 6.35  $\mu\text{m}$ . In case of the perspex workpiece, the face  $S_2$  was machined for datum  $R_a$  of 0.85  $\mu\text{m}$ , 2.15  $\mu\text{m}$  and 6.35  $\mu\text{m}$ . Perpendicularity is measured in the CMM. Figure 5.6 shows the variation of perpendicularity tolerance with datum roughness for cast iron and perspex work materials. For both the cases, it is observed that perpendicularity tolerance decreases with increase in datum roughness. A rough datum with  $R_a$  value of 6.35  $\mu\text{m}$  provided a better perpendicularity tolerance compared to lower datum  $R_a$  values. As described in the previous subsection, the maximum parallelism tolerance was obtained for an intermediate value of datum surface roughness. However, the maximum perpendicularity tolerance is obtained at the lowest value of datum surface roughness.

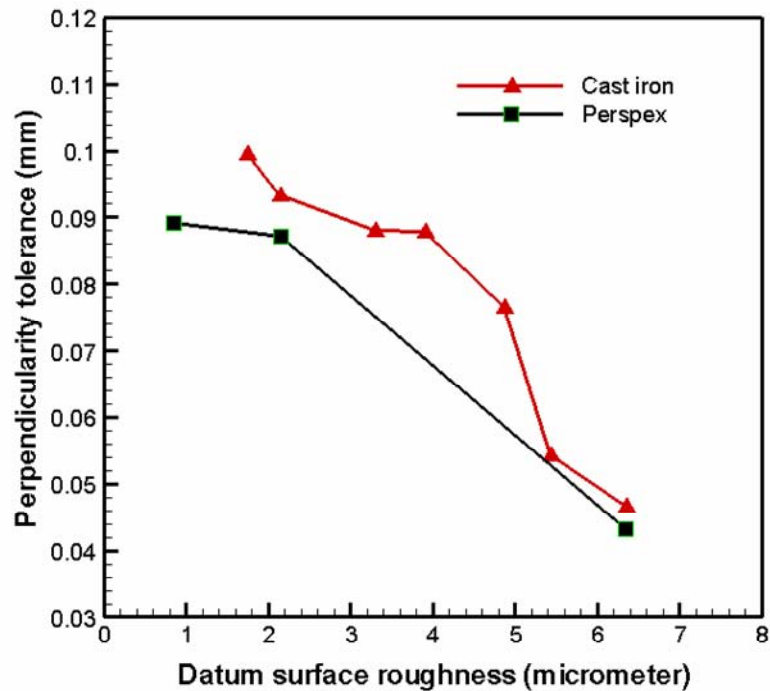


(a)



(b)

**Figure 5.5.** Variation of Z coordinate differences with sample points for machining of perspex workpiece on vertical milling machine (a) along D<sub>1</sub> (b) along D<sub>2</sub>



**Figure 5.6.** Variation of perpendicularity tolerance with datum roughness

### 5.3.3 Statistical Analysis of the Experimental Results

In a machining process, some inherent statistical variation is always present. To account for the statistical variations, a test of hypothesis may be employed. In view of this, 5 replicates of each experiment are carried out and statistical analysis is conducted. Sample mean, standard deviation and range are calculated for each sample for parallelism and perpendicularity. A test of hypothesis is used to check the significance of the variability of the results [Logothetis, 1997]. A brief description of hypothesis testing is provided below.

Sometimes experimental results are strongly believed to be true. But after taking a sample, it is observed that data of one sample does not wholly tally with the data of another sample. The difference may be due to the original belief being wrong or the sample being slightly one sided. Tests are, therefore, needed to distinguish between the two possibilities. These tests tell about the likely possibilities and reveal whether or not the difference can be due to chance elements. If the difference is not due to chance elements, it is significant, and therefore these tests are called test of significance. The whole procedure is known as ‘testing of hypothesis’. A hypothesis is a statement supposed to be true till it is proved false.

Another measure of the variability of the experimental results is coefficient of variation (CV), which is computed as

$$CV = \frac{s}{\bar{x}} \times 100. \quad (5.1)$$

where  $\bar{x}$  and  $s$  are the sample mean and standard deviation. CV provides a general feeling about the performance of a method.

#### 5.3.3.1 Parallelism

Tables 5.1 and 5.2 show the results of replicate experiments for the machining of cast iron on the vertical milling machine. Table 5.1 shows the maximum difference between  $Z$  coordinates of two points along diagonal  $D_1$  for 5 replicates. The mean ( $\bar{x}$ ), standard deviation ( $s$ ), and range for each datum roughness are calculated. In this case, the maximum value of coefficient of variation is 3.66 % for a datum surface roughness of  $5.43 \mu\text{m}$  [Appendix A]. Hence, the variability between the replicate experiments is low. Table 5.2 shows the maximum difference between  $Z$  coordinates of two points along diagonal  $D_2$  for five replicates. Along  $D_2$  the  $Z$  coordinates do not vary much. Hence, the maximum difference between the two points is markedly smaller. The maximum CV value is 15.68 % for the case of datum surface roughness of  $6.35 \mu\text{m}$  [Appendix A]. Tables 5.3 and 5.4 show the results of replicate experiments for the machining of perspex on the vertical milling machine. In Table 5.3, the maximum value of CV is 4.36 % for the case of datum surface roughness of  $6.35 \mu\text{m}$  [Appendix A]. In Table 5.4, the maximum value of CV is 9.09 % for the case of datum surface roughness of  $2.15 \mu\text{m}$  [Appendix A].

To ascertain whether the differences among the parallelism tolerance for the lowest and highest datum roughness cases are significant or not, a test of hypothesis is employed. The Student's  $t$ -test for small samples is used [Appendix B]. Let  $\bar{x}_H$  and  $\bar{x}_L$  be the mean of maximum parallelism tolerance for the highest and the lowest datum roughness cases respectively. The corresponding standard deviations are  $s_H$  and  $s_L$ . Sample size is  $n$  for both the cases. The null hypothesis is taken as:

$H_0$ : The difference in parallelism tolerance for low and high datum roughness is not significant, *i.e.*

$$\bar{x}_H - \bar{x}_L = 0 \quad (5.2)$$

The alternative hypothesis considered is

$H_1$ : Parallelism tolerance for high datum roughness is lower than that of low datum roughness, *i.e.*,

$$\bar{x}_H < \bar{x}_L \quad (5.3)$$

The  $t$  value for the case of equal sample sizes is given by

$$t = \frac{\bar{x}_L - \bar{x}_H}{\sqrt{\frac{(s_L^2 + s_H^2)}{n}}} \quad (5.4)$$

At the 5% significance level and for 8 degrees of freedom, the critical value of  $t$  denoted as  $t_{0.05}$  is 1.86 for one-sided test [Logothetis, 1997]. Considering the cases between datum roughness 1.74  $\mu\text{m}$  and 6.35  $\mu\text{m}$ , the value of  $t$  in the  $t$ -test is found to be 80.94 which is much higher than the value of  $t_{0.05}$  [Appendix B]. As  $|t| > t_{0.05}$ , the null hypothesis is rejected. Conclusion can be drawn at 95% confidence interval that there is significant difference in parallelism tolerance for low and high datum roughness cases. Parallelism tolerance for high datum roughness is lower than that for low datum roughness. The  $t$ -distribution calculations for all the cases of machining of cast iron and perspex are presented in Appendix B.

**Table 5.1.** Maximum Z coordinate difference between two points along D<sub>1</sub> for cast iron workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
1.74	0.1682	0.1665	0.1599	0.1698	0.1625	5	0.1654	0.0041	0.0099
2.14	0.1903	0.1952	0.1939	0.2014	0.2021	5	0.1966	0.0051	0.0118
3.29	0.2267	0.2198	0.2194	0.2187	0.2199	5	0.2209	0.0033	0.0080
3.90	0.2318	0.2325	0.2311	0.2345	0.2301	5	0.2320	0.0017	0.0044
4.86	0.0909	0.0887	0.0895	0.0873	0.0899	5	0.0893	0.0014	0.0036
5.43	0.0346	0.0339	0.0365	0.0358	0.0369	5	0.0355	0.0013	0.0030
6.35	0.0162	0.0164	0.0170	0.0165	0.0169	5	0.0166	0.0003	0.0008

**Table 5.2.** Maximum Z coordinate difference between two points along D<sub>2</sub> for cast iron workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
1.74	0.0280	0.0288	0.0331	0.0326	0.0264	5	0.0300	0.0032	0.0067
2.14	0.0277	0.0223	0.0302	0.0252	0.0266	5	0.0264	0.0029	0.0079
3.29	0.0268	0.0301	0.0291	0.0264	0.0275	5	0.0280	0.0016	0.0037
3.90	0.0323	0.0259	0.0301	0.0317	0.0312	5	0.0302	0.0026	0.0064
4.86	0.0414	0.0361	0.0339	0.0416	0.0354	5	0.0377	0.0036	0.0077
5.43	0.0306	0.0250	0.0299	0.0301	0.0294	5	0.0290	0.0023	0.0056
6.35	0.0137	0.0144	0.0143	0.0196	0.0147	5	0.0153	0.0024	0.0059

**Table 5.3.** Maximum Z coordinate difference between two points along D<sub>1</sub> for perspex workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
0.85	0.2989	0.2954	0.2963	0.2985	0.2978	5	0.2973	0.0020	0.0035
2.15	0.3099	0.3008	0.3053	0.3067	0.3073	5	0.3060	0.0033	0.0091
6.35	0.0989	0.1023	0.1096	0.1087	0.1078	5	0.1055	0.0046	0.0107

**Table 5.4.** Maximum Z coordinate difference between two points along D<sub>2</sub> for perspex workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
0.85	0.0389	0.0416	0.0397	0.0392	0.0381	5	0.0395	0.0013	0.0035
2.15	0.0402	0.0409	0.0407	0.0412	0.0406	5	0.0407	0.0037	0.0010
6.35	0.0326	0.0331	0.0340	0.0348	0.0341	5	0.0337	0.0008	0.0022

### 5.3.3.2 Perpendicularity

Table 5.5 shows the perpendicularity tolerance for cast iron workpiece for 5 replicates with their mean, standard deviation and range for each case of datum roughness. In this case, the maximum value of CV is 1.98 % for a datum surface roughness of 5.43  $\mu\text{m}$  indicating a very small variation among the replicate experiments [Appendix A]. Table 5.6 shows the perpendicularity tolerance for perspex workpiece for 5 replicates. Here too, the maximum value of CV is 1.58 % for a datum surface roughness of 6.35  $\mu\text{m}$ , thus confirming a good repeatability [Appendix A].

It is observed that in both the cases, rough datum is providing a better perpendicularity tolerance. A test of hypothesis shows a significant difference

between the perpendicularity tolerances at low and high datum surface roughness cases [Appendix B].

**Table 5.5.** Perpendicularity tolerance with varying datum roughness for cast iron workpiece

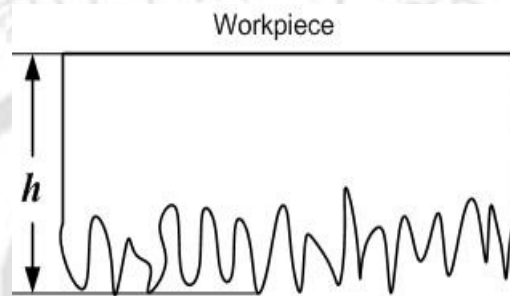
Datum roughness	Replicate1	Replicate2	Replicate3	Replicate4	Replicate5	Sample size	Sample mean	Standard deviation	Range
$R_a$ ( $\mu\text{m}$ )	(mm)	(mm)	(mm)	(mm)	(mm)	$N$	$\bar{x}$ (mm)	$s$ (mm)	(mm)
1.74	0.0996	0.0968	0.0993	0.0976	0.0989	5	0.0984	0.0012	0.0028
2.14	0.0934	0.0945	0.0936	0.0962	0.0957	5	0.0947	0.0012	0.0028
3.29	0.0881	0.0884	0.0879	0.0873	0.0879	5	0.0879	0.0004	0.0011
3.90	0.0879	0.0874	0.0881	0.0869	0.0877	5	0.0876	0.0005	0.0012
4.86	0.0766	0.0781	0.0779	0.0788	0.0787	5	0.0782	0.0005	0.0022
5.43	0.0543	0.0568	0.0561	0.0557	0.0545	5	0.0555	0.0011	0.0025
6.35	0.0467	0.0473	0.0455	0.0478	0.0469	5	0.0468	0.0008	0.0023

**Table 5.6.** Perpendicularity tolerance with varying datum roughness for perspex workpiece

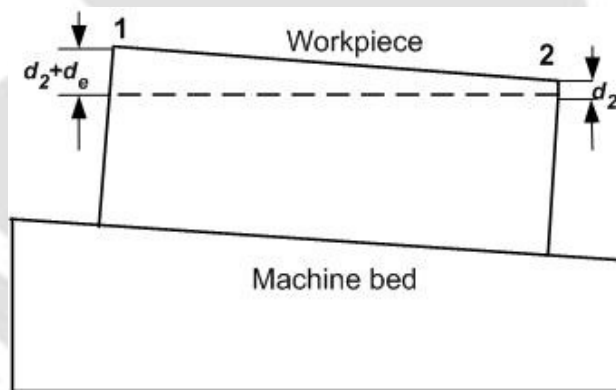
Datum roughness	Replicate1	Replicate2	Replicate3	Replicate4	Replicate5	Sample size	Sample mean	Standard deviation	Range
$R_a$ ( $\mu\text{m}$ )	(mm)	(mm)	(mm)	(mm)	(mm)	$N$	$\bar{x}$ (mm)	$s$ (mm)	(mm)
0.85	0.0891	0.0889	0.0897	0.0891	0.0895	5	0.0893	0.0003	0.0008
2.15	0.0872	0.0881	0.0870	0.0879	0.0883	5	0.0877	0.0006	0.0013
6.35	0.0433	0.0446	0.0452	0.0439	0.0442	5	0.0442	0.0007	0.0019

## 5.4 A Theoretical Model for Explaining the Observations

To understand and explain the above observations, a qualitative mathematical model is developed considering the cases of smooth and rough datum. A rough surface has vertical deviations in the form of peaks and valleys from the nominal surface as shown in Figure 5.7. When the workpiece is placed on the machine bed, the contact is between the high asperities of the rough datum and the smooth machine bed.



**Figure 5.7.** An exaggerated view of the rough datum



**Figure 5.8.** A workpiece kept on an inclined machine bed

During machining, the cutter may not move parallel to the top face  $S_1$  because of a number of factors. However, the effect is equivalent to machining of a workpiece placed on an inclined machine bed as shown in Figure 5.8, while the cutter moves horizontally. Therefore, more depth of cut is realized at point 1 than at point 2. Let the initial height of the workpiece be  $h$  and effective depths of cut at the points 1 and 2 be  $d_2 + d_e$  and  $d_2$  respectively, where  $d_e$  is the additional depth of cut realized at point 1 due to inclination of the bed. Two cases are considered.

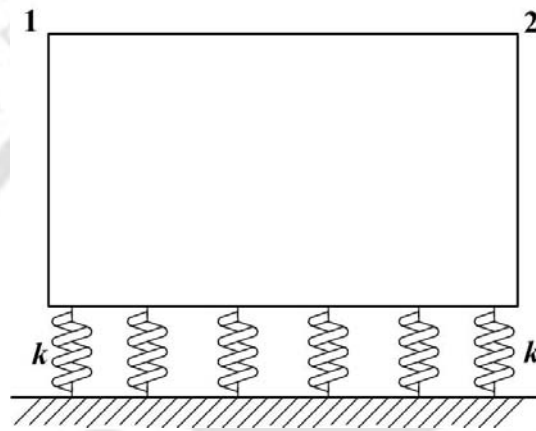
(i) Case 1 (Smooth Datum)

A smooth datum behaves as a rigid body. After machining of the top face, the difference in heights between points 1 and 2 is given by

$$\{h - (d + d_e)\} - (h - d) = -d_e \quad (5.5)$$

where  $d$  is the applied depth of cut. Thus, a parallelism error of  $d_e$  is obtained due to inherent error of the machine.

(ii) Case 2 (Rough Datum)



**Figure 5.9.** Hypothetical datum with springs

A number of researchers have modelled workpiece-fixture contact surface as springs [Shawki and Abdel-Aal, 1965, 1966a, 1966b, Yeh and Liou, 1999]. For accurate knowledge of workpiece-fixture contact conditions, material properties, contact area, hardness of material and surface finish are to be considered. Shawki and Abdel-Aal [1965, 1966a, 1966b] developed a workpiece-fixture contact model by experimentally observing the relation between force and deformation at workpiece-fixture contact considering surface finish, hardness and contact area. The equation to express the deformation,  $\delta$  at the workpiece-fixture contact surface under applied pressure  $p$  is given by:

$$\delta = (a_1 - a_2 H_B + b_1 A_c + b_2 R_h) p^n, \quad (5.6)$$

where  $H_B$  is the Brinell hardness value for the workpiece,  $A_c$  is the contact area and  $R_h$  is the surface roughness of the workpiece and  $n$  is the index depending on the material [Shawki and Abdel-Aal, 1966b]. It is evident from Eq. (5.6) that with an increase in surface roughness, the stiffness of the workpiece decreases.

The present work models the asperities of rough datum as springs (Figure 5.9) which deflect due to the cutting forces. If  $\delta_1$  is the deflection at point 1 and  $\delta_2$  is the deflection at point 2,  $\delta_1$  is greater than  $\delta_2$  as cutting force at point 1 is more than at point 2. Therefore, the effective depth of cut at point 1 is much less than desired depth of cut. However, effective depth of cut is only slightly less than desired depth of cut at point 2. Now the difference in height between points 1 and 2 with rough datum is given by

$$\{h - (d + d_e - \delta_1)\} - \{h - (d - \delta_2)\} = -d_e + (\delta_1 - \delta_2) \quad (5.7)$$

where the error magnitude of height is  $d_e + (\delta_2 - \delta_1)$ . As  $(\delta_2 - \delta_1)$  is negative, the difference in magnitude in heights of the top face in case of rough datum gets reduced compared to smooth rigid datum.

Considering cutting force  $F$  to be a function of effective depth of cut, force balance at points 1 and 2 provides

$$F(d + d_e - \delta_1) = k\delta_1 \quad (5.8)$$

$$F(d - \delta_2) = k\delta_2 \quad (5.9)$$

Cutting force  $F$  at points 1 and 2 can be expanded using Taylor series. Considering that  $d_e$ ,  $\delta_1$  and  $\delta_2$  are much smaller compared to  $d$ , only the first two terms of the Taylor series may be taken. Thus,

$$F(d + d_e - \delta_1) = F(d) + k_p(d_e - \delta_1) \quad (5.10)$$

$$F(d - \delta_2) = F(d) - k_p\delta_2 \quad (5.11)$$

where  $k_p$  is the proportionality constant. Substituting the expression of  $F$  in equations (5.8) and (5.9) from equations (5.10) and (5.11), the deflections of the springs at points 1 and 2 are

$$\delta_1 = \frac{F(d) + k_p d_e}{k + k_p} \quad (5.12)$$

$$\delta_2 = \frac{F(d)}{k + k_p} \quad (5.13)$$

Now,

$$\text{Height at point 1} = h - (d + d_e - \delta_1) \quad (5.14)$$

$$\text{Height at point 2} = h - (d - \delta_2) \quad (5.15)$$

Substituting the values of  $\delta_1$  and  $\delta_2$  in Equations (5.14) and (5.15),

$$\text{Height at point 1} = h - d + \frac{F(d)}{k + k_p} - \frac{kd_e}{k + k_p} \quad (5.16)$$

$$\text{Height at point 2} = h - d + \frac{F(d)}{k + k_p} \quad (5.17)$$

From equations (5.16) and (5.17),

$$\text{Difference in heights between points 1 and 2} = \frac{kd_e}{k + k_p}, \quad (5.18)$$

which is always less than  $d_e$  as  $k$  is less than  $k + k_p$ . This explains that the rough datum may provide a lesser parallelism tolerance than the smooth datum. A similar analysis can be carried out to show that the perpendicularity tolerance may get reduced due to roughness of the datum.

## 5.5 Experimental Verification of the Proposed Theoretical Model

This section presents some experiments performed to verify the validity of the proposed theoretical model to study the effect of datum surface roughness on parallelism and perpendicularity.

### 5.5.1 Experiments in a Universal Testing Machine

The proposed theoretical model establishes that the high value of datum surface roughness increases the flexibility of datum. With rough datum, deflection is more and parallelism tolerance is less. To ascertain the effect of the vertical component of the cutting force on the deflection of the workpiece, a number of simulation experiments were carried out in a universal testing machine (UTM, INSTRON 8801). The machining condition in milling was approximated by using a rod of 20 mm diameter (equal to the diameter of the end mill cutter) to apply the compressive load. The rod was fitted in the upper gripper of the UTM and used to apply the load symmetrically at a point on the top surface of the workpiece placed on the UTM. During actual machining of the workpiece, clamping device used was a machine vice with a large contact area and the clamping force applied was distributed.

Moreover, use of excessive clamping force was avoided to prevent workpiece deformation. In the UTM, load applied was concentrated at a point and no clamping was employed. As clamping force during actual machining is of a distributed nature and is of low magnitude, the possible effect of clamping may not be significant.

The actual static vertical cutting force components measured for cast iron workpiece at depths of cut 0.2 mm and 0.4 mm were 36 N and 68 N with rough datum (6.35  $\mu\text{m}$ ) and 34 N and 59 N with smooth datum (1.74  $\mu\text{m}$ ). The corresponding forces for perspex were 26 N and 45 N with rough datum (6.35  $\mu\text{m}$ ) and 23 N and 44 N with smooth datum (0.85  $\mu\text{m}$ ). In the UTM, a compressive force of 36 N was applied at a point on the cast iron workpiece with rough datum and the corresponding deflection was found to be 0.21 mm. The same force produced a deflection of 0.04 mm with smooth datum. For a compressive force of 68 N, deflection recorded was 0.25 mm with rough datum whereas the deflection is 0.06 mm with a smooth datum. It is observed that with the same amount of compressive forces, 36 N and 68 N, the deflections with rough datum are more than that with smooth datum by the amounts of 0.17 mm and 0.19 mm respectively. Similar experiments on perspex revealed that deflections with rough datum are more by the amounts of 0.24 mm and 0.25 mm than with smooth datum. From the above observations, it can be concluded that with rough datum, the deflection of the workpiece is more. In the present work, rough datum is able to deflect the workpiece approximately in the order of 0.2 mm and compensate for the machine inherent error,  $d_e$ .

It is observed that the highest parallelism tolerance is 0.23 mm (Figure 5.3) for cast iron workpiece and 0.31 mm for perspex workpiece (Figure 5.5) with comparatively smooth datum. With rough datum, this difference is much less as the vertical component of the cutting force produces more deflection and compensates for the machine inherent error  $d_e$  to the order of approximately 0.2 mm. The results of the above simulation experiments in the UTM support the validity of the proposed model described in Section 5.4. Although it is a crude method of comparison, the findings support that it is possible for the rough datum to produce

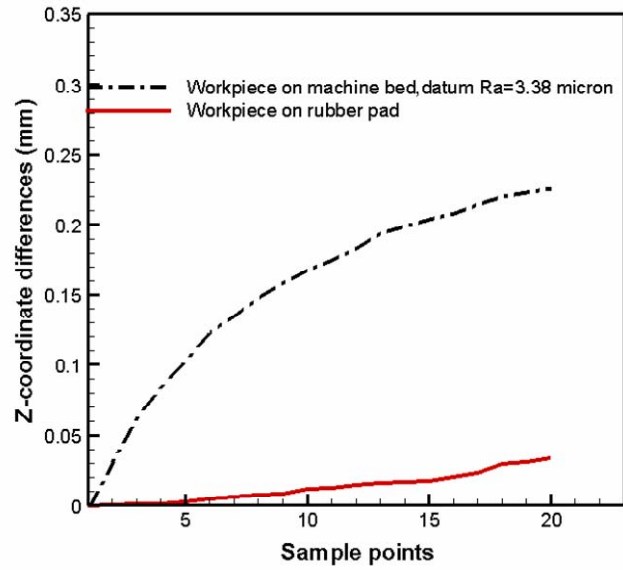
deflections approximately of the order of 0.2 mm and reduce parallelism tolerance by compensating for the machine inherent error.

### 5.5.2 Experiments on Workpiece Supported on a Rubber Pad

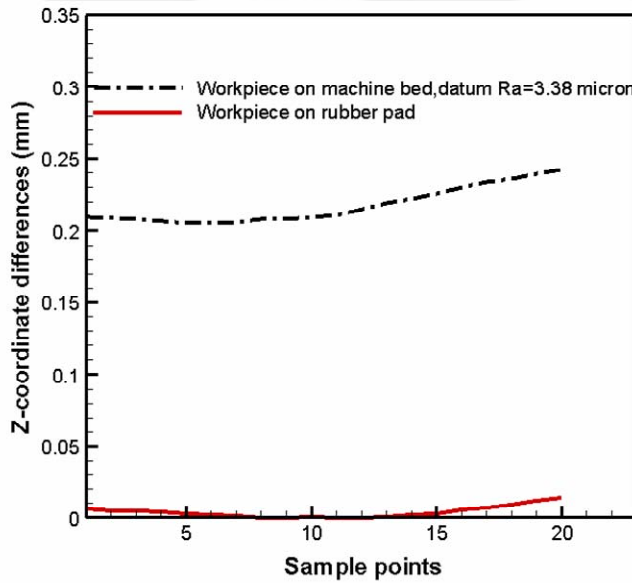
To understand further the developed hypothesis for rough datum, two more sets of experiments were done by inserting a 3 mm thickness rubber pad between the cast iron workpiece and machine bed. The top face was machined once by keeping the workpiece on a 3 mm thickness rubber pad and then by keeping it directly on the machine bed. The experimental procedure described in Section 5.2 is repeated in the vertical milling machine both for parallelism and perpendicularity.

Figure 5.10 shows the differences in the  $Z$  coordinate values of the top face along diagonals  $D_1$  and  $D_2$  for datum roughness of  $3.38 \mu\text{m}$  for two cases: workpiece placed directly on the machine bed and workpiece resting on the rubber pad. Figure 5.11 shows the results of a similar set of experiment with datum roughness of  $2.27 \mu\text{m}$ . It is observed from Figures 5.10 and 5.11 that at same datum roughness, differences in the  $Z$  coordinate values of the points along diagonals  $D_1$  and  $D_2$  are less when the workpiece rests on the rubber pad. The rubber pad allows the workpiece to deflect elastically. Rough datum and rubber pad datum shows similar type of behaviour and the differences in the  $Z$  coordinate values are less compared to smooth datum which behaves as a rigid body. Perpendicularity tolerance is 0.0483 mm with the rubber pad at datum roughness of  $3.38 \mu\text{m}$ , which is lower than the perpendicularity tolerance of 0.0984 mm with the smooth datum ( $1.74 \mu\text{m}$ ).

It is to be noted that owing to the elastic deformation of the rubber pad, the effective depth of cut gets reduced, as evident from equation (5.18). Therefore, in order to maintain proper dimensional tolerance, this effect has to be compensated by providing more depth of cut. Appropriate amount of compensation can be determined experimentally.

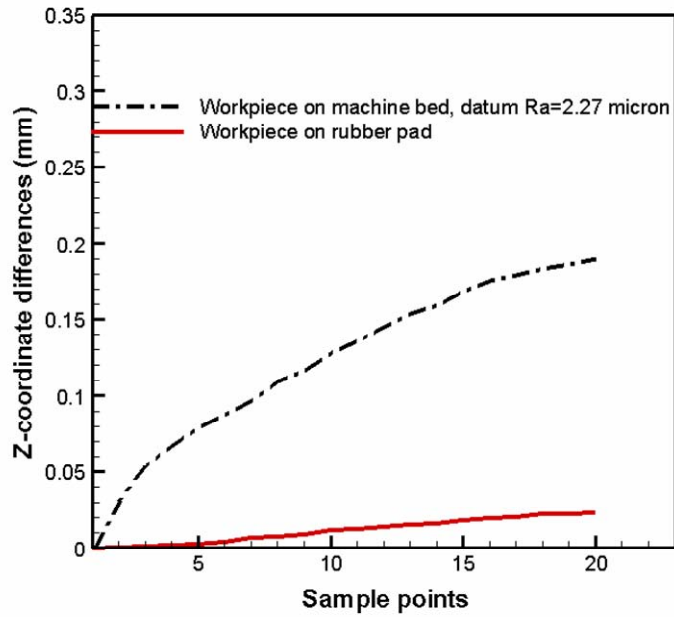


(a)

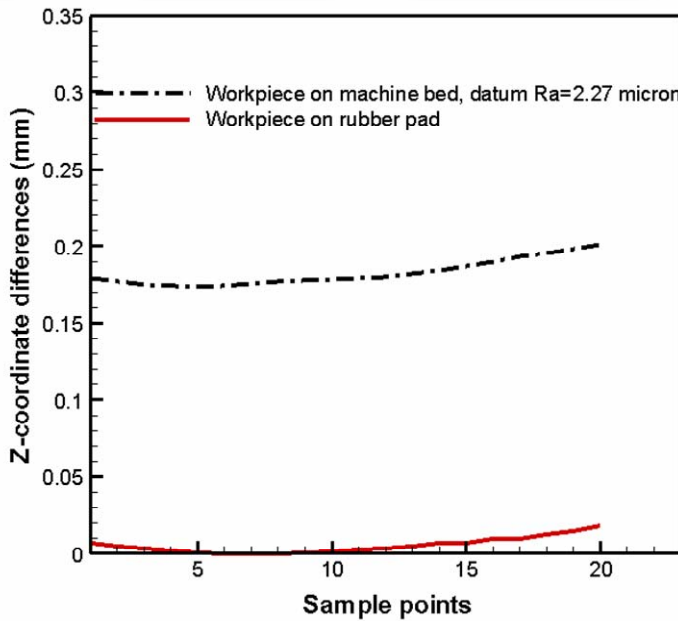


(b)

**Figure 5.10.** Variation of Z coordinate differences with sample points for cast iron workpiece with rubber pad on vertical milling machine (a) along  $D_1$  (b) along  $D_2$  for Experiment 1



(a)



(b)

**Figure 5.11.** Variation of Z coordinate differences with sample points for cast iron workpiece with rubber pad on vertical milling machine (a) along  $D_1$  (b) along  $D_2$  for Experiment 2

## 5.6 Incorporation of the Knowledge Gathered from the Experimental Study into the Setup Planning Expert System

Although it is believed that a smooth datum should be used when geometric tolerance requirements are tight, the present experimental study reveals that it may not be always true. Sometimes, a rough datum may provide better geometric tolerances. Moreover, machining a surface to a smooth finish requires extra cost. Therefore, the knowledge gathered from the experimental study is incorporated into the knowledge-base of the setup planning expert system in the form of IF–THEN rules. This knowledge is used to decide the required roughness of a datum face for achieving a particular tolerance level. The pseudo code for an IF–THEN rule is given below. Here  $p$  is the desired parallelism tolerance,  $p^*$  and  $p^{**}$  are the limits of the range in which  $p$  lies,  $R_a$  is the datum roughness, and  $R_a^*$  is the minimum required value of datum roughness for achieving the desired parallelism tolerance  $p$ .

IF (*desired parallelism tolerance  $p$  lies between  $p^*$  and  $p^{**}$* )  
 THEN (*datum roughness  $R_a$  should be between  $R_a^*$  and  $6 \mu\text{m}$* )

If  $R_a$  value goes below  $R_a^*$ , i.e.  $R_a < R_a^*$ , the obtained parallelism tolerance may become more than the desired value. Based on the desired value of parallelism tolerance,  $R_a^*$  can be obtained from Table 5.1. Although the maximum datum roughness value is  $6.35 \mu\text{m}$  in Table 5.1, it is considered a bit high roughness value for datum surface based on aesthetic consideration, etc. So, the upper limit of datum roughness  $R_a$  is kept as  $6 \mu\text{m}$ . The following rules are formed based on the data provided in Table 5.1:

```
(Defrule::selecting- datum-roughness-rule1
  (bind ?Ra* 5.43)
  (bind ?p* 0.02)
  (bind ?p** 0.04)
  (test (and(>= ?p ?p*)( <= ?p ?p** )))
=> (assert (and (>= ?Ra ?Ra*) (<= ?Ra 6 ))))
```

It states that if the desired parallelism tolerance ( $?p$ ) is within 0.02–0.04 mm, then the datum surface roughness ( $?R_a$ ) should lie in the range 5.43–6  $\mu\text{m}$ . Here 5.43  $\mu\text{m}$  is the minimum value of  $R_a$ , i.e.  $R_a^*$ .

*(Defrule::selecting- datum-roughness-rule2*

*(bind ?R<sub>a</sub>\* 4.86)*

*(bind ?p\* 0.04)*

*(bind ?p\*\* 0.09)*

*(test (and(> ?p ?p\*)( <= ?p ?p\*\* )))*

*=> (assert (and (>= ?R<sub>a</sub> ?R<sub>a</sub>\*) (<= ?R<sub>a</sub> 6 ))))*

It states that if the desired parallelism tolerance ( $?p$ ) is within 0.04–0.09 mm, then the datum surface roughness ( $?R_a$ ) should lie in the range 4.86–6  $\mu\text{m}$ . Here 4.86  $\mu\text{m}$  is the minimum value of  $R_a$ , i.e.  $R_a^*$ .

*(Defrule::selecting- datum-roughness-rule3*

*(bind ?R<sub>a</sub>\* 4.86)*

*(bind ?p\* 0.09)*

*(bind ?p\*\* 0.17)*

*(test (and(> ?p ?p\*)( <= ?p ?p\*\* )))*

*=> (assert (= ?R<sub>a</sub> 1.74) | (and (>= ?R<sub>a</sub> ?R<sub>a</sub>\*) (<= ?R<sub>a</sub> 6 ))))*

It states that if the desired parallelism tolerance ( $?p$ ) is within 0.09–0.17 mm, then there are two options for selecting datum surface roughness ( $?R_a$ ). Either datum roughness can be 1.74  $\mu\text{m}$  or it should lie in the range 4.86–6  $\mu\text{m}$ .

*(Defrule::selecting- datum-roughness-rule4*

*(bind ?p\* 0.17)*

*(bind ?p\*\* 0.20)*

*(test (and(> ?p ?p\*)( <= ?p ?p\*\* )))*

*=> (assert (and (>= ?R<sub>a</sub> 1.74) (<= ?R<sub>a</sub> 2.14) | (and (>= ?R<sub>a</sub> 4.86) (<= ?R<sub>a</sub> 6 ))))*

It states that if the desired parallelism tolerance ( $?p$ ) is within 0.17–0.20 mm, then there are two options for selecting datum surface roughness ( $?R_a$ ). Datum roughness should lie either in the range 1.74–2.14  $\mu\text{m}$  or in the range 4.86–6  $\mu\text{m}$ .

*(Defrule::selecting- datum-roughness-rule5*

*(bind ?p\* 0.20)*

*(bind ?p\*\* 0.22)*

*(test (and(> ?p ?p\*)( <= ?p ?p\*\* )))*

*=> (assert (and (>=?R<sub>a</sub> 1.74) (<= ?R<sub>a</sub> 3.29) | (and (>= ?R<sub>a</sub> 4.86) (<= ?R<sub>a</sub> 6 ))))*

It states that if the desired parallelism tolerance (*?p*) is within 0.20–0.22 mm, then there are two options for selecting datum surface roughness (*?R<sub>a</sub>*). Datum roughness should lie either in the range 1.74–3.29  $\mu\text{m}$  or in the range 4.86–6  $\mu\text{m}$ .

*(Defrule::selecting- datum-roughness-rule6*

*(bind ?R<sub>a</sub>\* 1.74)*

*(bind ?p\* 0.22)*

*(bind ?p\*\* 0.23)*

*(test (and(> ?p ?p\*)( <= ?p ?p\*\* )))*

*=> (assert (and (>= ?R<sub>a</sub> ?R<sub>a</sub>\*) (<= ?R<sub>a</sub> 6 ))))*

It states that if the desired parallelism tolerance (*?p*) is within 0.22–0.23 mm, then datum surface roughness (*?R<sub>a</sub>*) should lie in the range 1.74–6  $\mu\text{m}$ .

These rules will give the required datum surface roughness for attaining a desired tolerance level. The process parameters are to be selected by the process planner for achieving that datum surface roughness. The actual machining process is monitored on the shop floor according to the conditions provided in the checklist (Figure 4.3, Chapter 4). If some deviation from the expected outcome is detected, adaptive learning strategy (Section 4.4, Chapter 4) is applied and the required modifications are made. For example, if required tolerance is not achieved with a particular datum surface roughness, the rule-base is to be checked and the datum surface roughness may have to be increased/decreased depending on the desired tolerance. Thus the setup planning expert system keeps learning from the actual shop floor feedback and keeps updating its knowledge-base.

## 5.7 Summary

In setup planning, selection of proper datum is essential for attaining the specified tolerances of the machined component. In this work, effect of datum surface roughness on two geometric tolerances, *viz.* parallelism and perpendicularity is studied with a series of experiments done in a vertical milling machine and a universal milling machine. Statistical analysis of the experimental results is carried out. It is observed from the experiments that for smooth datum, parallelism and perpendicularity tolerances are more than for rough datum. Some experiments were conducted in the UTM to verify the validity of the proposed model and the results are in good agreement with the assumptions made for modelling. Similarly, parallelism and perpendicularity tolerances with rubber pad are lesser than for smooth datum. This is because when the rubber pad is used, datum becomes flexible and allows elastic deformation of the workpiece.

In setup planning, the appropriate datum surface roughness should be chosen judiciously. It has been a common practice to have a smooth datum when geometric tolerance requirements are tight. However, the present study reveals that it need not always be the case. A rough datum may provide better geometric tolerances due to two opposing effects, machine tool error and elastic deflection of the workpiece. It is difficult to obtain a quantitative model for predicting the geometric tolerances as a function of datum roughness, because of the unique characteristics of different machine tools and surfaces. Although a skilled machinist can estimate the required datum surface roughness based on his experience, it is always desirable to have an automated system that can predict the appropriate datum roughness values for a particular machining case. In view of it, the knowledge gained from the experimental study is incorporated into the setup planning expert system in the form of IF–THEN rules. The knowledge is used to decide the datum surface roughness for achieving a particular tolerance level. It is suggested that based on the shop floor feedback, the rules can be updated and the setup planning expert system keeps learning from experience.

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## Incorporation of Fixturing Requirements in Setup Planning

### 6.1 Introduction

Setup planning is a critical component of process planning for machining a component. The existing setup planning systems provide the optimum number of setups to machine a component, operation sequences, setup sequences, and datum for each setup. However, the output of the traditional setup planning approaches is limited and insufficient for upstream process planning activity such as fixture design. To generate a robust and practical solution for machining a component, setup, fixturing and machining constraints are to be considered simultaneously. It is essential to estimate the range of process parameters, machining forces and clamping forces during setup planning stage considering the feasibility of fixturing. In absence of this, the independent fixture design module may fail to generate feasible fixture plans leading to the need of redesigning of setups.

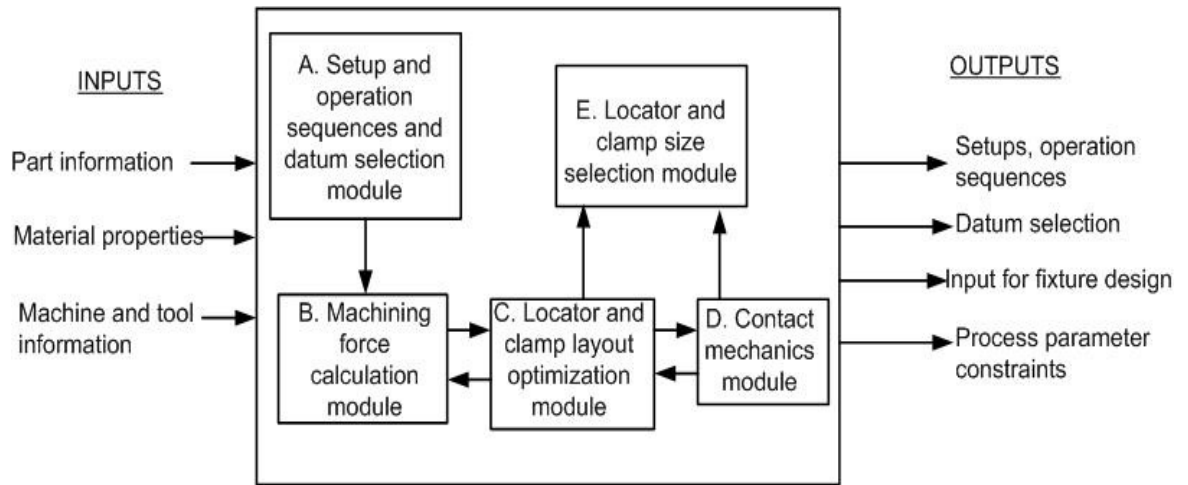
There are a number of research efforts on setup planning without considering fixturing aspect. A detailed discussion of these efforts is presented in Chapter 2. In these approaches, different researchers have given importance to different issues, *viz.* tolerance achievement, adaptability, and optimization of setup plans.

There are some attempts in the literature to develop setup plans considering fixturing aspect [Boerma and Kals, 1988; Boerma and Kals, 1989; Young and Bell, 1991; Sakurai, 1992; Wu and Zhang, 1998; Wu and Chang, 1998; Zhang and Lin, 1999; Tseng, 1999; Joneja and Chang, 1999; Kaya and Ozturk, 2001; Huang and Xu, 2003; Gologlu, 2004; Bansal *et al.*, 2008; Hebbal and Mehta, 2008; and Stampfer, 2009]. A review of these research works can be found in Chapter 2. However, there are limited attempts on developing a setup planning strategy that provides sufficient input to the fixture design and further process planning. Most of the works in the literature considering fixturing aspects [Boerma and Kals, 1988,

1989; Wu and Zhang, 1998; Wu and Chang, 1998; Zhang and Lin, 1999; Joneja and Chang, 1999; Huang and Xu, 2003; Gologlu, 2004; Hebbal and Mehta, 2008; and Stampfer, 2009] deal with the conceptual fixture design phase by identifying the datum features. The aspects relating to position of the locators and clamps, machining force, clamping force, and range of process parameters require more attention. These issues are not covered in detail in the existing setup planning approaches. In view of it, the objective of this work is to incorporate fixturing requirements into the setup planning expert system for machining of prismatic parts. In addition to the setup planning information, the system now can provide the following output: (i) recommended depth of cut/feed in fuzzy form, (ii) machining and clamping forces in fuzzy form, (iii) approximate optimal locator and clamp layout and (iv) sizes of the locators and clamps. The fixture designer can further optimize the fixture plan by taking input from the setup planning module. This methodology helps in improving the overall efficiency of the process plan. Moreover, the uncertainties associated with the work material, clamp material and clamping torque are considered by means of fuzzy arithmetic.

## **6.2 The Architecture of the Fixturing Information Generation Module**

A block diagram representation of the setup planar with the detail of fixturing information generation module is shown in Figure 6.1. The fixturing information generation module contains the sub-modules B, C, D and E and it takes input from module A (described in Chapter 3) that generates number of setups, operation sequences, and datum for each setup. B is machining force calculation module, module C generates optimized locator and clamp layout, D is the workpiece-fixture contact module, and module E selects locator and clamp sizes.



**Figure 6.1.** The setup planar with the detailed fixturing information generation module

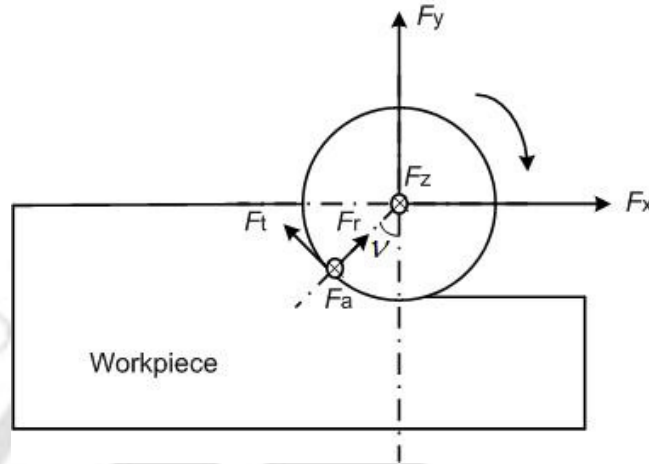
### 6.2.1 Setups, Operation Sequence and Datum Selection Module A

In module A, a fuzzy set based expert system is used for setup generation, operation sequencing and datum selection for machining of prismatic parts. The detail of module A are described in Chapter 3. It has a database, a rule-based knowledge-base and an inference engine. It has been implemented using the expert system shell CLIPS, an acronym for C Language Integrated Production System.

### 6.2.2 Approximate Machining Force Calculation Module B

Module B calculates approximate machining forces, *i.e.* cutting force components  $F_x$ ,  $F_y$  and  $F_z$  in the three Cartesian coordinate directions for the entire tool path for machining parts. Total specific energy approach is used for calculating the cutting forces. Cutting force calculation is best done in terms of total specific energy  $U_s$ , since it remains approximately constant for a given workpiece material operating under different cutting conditions [Shaw, 2005]. The resultant force on each cutting edge of a milling cutter has a tangential component  $F_t$  tangent to the tool perimeter, a radial component  $F_r$  along the radius of the cutter and an axial component  $F_a$  along the axis of the cutter. The force  $F_t$  is the main cutting force in milling and the other two components can be estimated from  $F_t$ . Radial component  $F_r$  is considered as  $0.3 F_t$  and the axial component  $F_a$  is  $F_r \tan \beta$ , where  $\beta$  is the helix

angle of the cutter [Stephenson and Agapiou, 2005]. Figure 6.2 shows the tangential, radial and axial force components  $F_t$ ,  $F_r$ , and  $F_a$ , and the cutting force components  $F_x$ ,  $F_y$  and  $F_z$  in the three Cartesian coordinate directions for a milling operation.



**Figure 6.2.** Cutting force components for a milling operation

The three Cartesian cutting force components  $F_x$ ,  $F_y$  and  $F_z$  can be expressed in terms of  $F_t$ ,  $F_r$  and  $F_a$  as [Stephenson and Agapiou, 2005]:

$$F_x = \sum_{j=1}^z \left[ \sum_{i=1}^{n_i} (F_{t_i} \cos(\nu_i - \psi_i) + F_{r_i} \sin(\nu_i - \psi_i)) \right], \quad (6.1)$$

$$F_y = \sum_{j=1}^z \left[ \sum_{i=1}^{n_i} (F_{t_i} \sin(\nu_i - \psi_i) - F_{r_i} \cos(\nu_i - \psi_i)) \right], \quad (6.2)$$

$$F_z = \sum_{j=1}^z \left[ \sum_{i=1}^{n_i} F_{a_i} \right], \quad (6.3)$$

where  $\nu$  is the engagement angle of the cutter,  $\psi$  is the angle of lag of a point on the cutting edge due to helical cutting edge,  $n_i$  is the number of teeth/flute of the cutter and  $z$  is the total number of axial elements comprising the axial depth of cut. The helix of a cutter provides a gradual engagement and disengagement of the cutting edge along the radial depth of cut contact. An unwound helical cutting edge is shown in Figure 6.3 which has a straight line contact along the axial depth of cut inclined at a helix angle  $\beta$ . Therefore, any point on the cutting edge at a distance  $y$  above the free end of the cutter will lag by an angle  $\psi$ . From Figure 6.3,

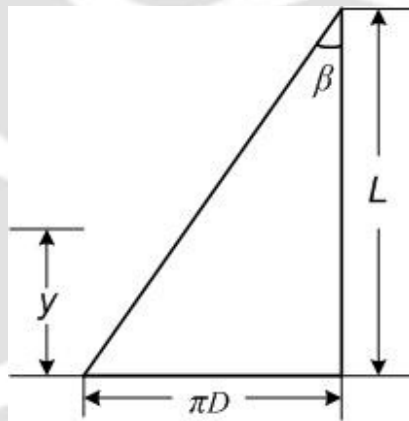
$$\tan \beta = \frac{\pi D}{L} \quad (6.4)$$

From Figure 6.3, the angular lag at a distance  $L$  from the free end of the cutter is  $2\pi$  radian. Therefore, angular lag  $\psi$  at a distance  $y$  from the free end of the cutter is given by

$$\psi = 2\pi \frac{y}{L} \quad (6.5)$$

Putting the value of  $L$  from Equation (6.4) in (6.5),

$$\psi = \frac{2y \tan \beta}{D} \quad (6.6)$$



**Figure 6.3.** Unwound helical cutting edge of a cutter

### 6.2.3 Locator and Clamp Layout Optimization Module C

Objective of a good fixture configuration design is to design and place the locators and clamps on the workpiece faces at such positions that the passive reaction forces are kept to a minimum. Module C finds the optimized locator and clamp layout which gives the smallest passive locator reaction forces maintaining the workpiece-fixture system stability and minimum deformation condition. Standard 3-2-1 locating principle for machining prismatic parts is followed in this work. The objective function is formulated to minimize the maximum  $L_2$  norm of locator reaction forces during machining and clamping. Clamping and machining

forces along with the part weight are the active known inputs and the locator reactions are the variables to be determined. The following constraints are used in the optimization problem:

Static equilibrium constraint: The necessary and sufficient condition to ensure stability of the workpiece is to satisfy the force and moment equilibrium equations where the forces and moments consist of the machining forces, clamping forces, part weight and locator reaction forces in the normal direction.

Workpiece-fixture contact constraint: The static equilibrium constraint keeps the workpiece stable during machining. However, it does not account for workpiece slippage or detachment from the locators resulting in negative or zero locator reaction force. Locators must be maintained in contact with the workpiece throughout the machining process to ensure complete immovability of the workpiece. A constraint that all locator reaction forces must be positive takes care of immovability of workpiece.

In this work, a frictionless contact between the workpiece and fixture elements is assumed. A frictionless analysis leads to a conservative and safer fixture design. Coulomb friction generates additional restraint to a workpiece-fixture system. Liao and Hu [2000] confirmed with a comparative analysis that a frictionless model predicts higher value of required clamping force than the model considering frictional effects.

The complete locator and clamp layout optimization model can be expressed mathematically as

$$\text{Minimize } \left[ \text{maximum of } \sum_{i=1}^6 R_i^2 \text{ over the entire cutting path} \right], \quad (6.7)$$

subject to the static equilibrium constraint

$$\sum F = 0, \sum M = 0 \quad (6.8)$$

and workpiece-fixture contact constraint

$$R_i > 0 \quad (6.9)$$

where  $R_i$  (  $i = 1$  to  $6$  ) is the locator reaction force in the normal direction, and  $\sum F$  and  $\sum M$  are net forces and moments due to machining forces, clamping

forces, part weight and locator reaction forces in the normal direction. Modular fixture elements can be used for this work. An additional constraint that the locating and clamping point coordinates take only discrete values is to be incorporated in the fixture layout optimization model given by Eq (6.7). An integer programming approach can be adopted.

#### 6.2.4 Workpiece-Fixture Contact Module D

Contact mechanics approach is used for modelling workpiece-fixture contact conditions in module D. Hertz's contact model can be used to represent the most common cases of contact between the workpiece and the fixture. It gives the contact area, contact deformation and total compressive load for two elastic bodies in contact [Appendix C]. The following key assumptions are made so that contact mechanics approach can be used for modelling [Johnson, 1985].

- The workpiece and fixture elements are linear elastic bodies.
- Workpiece-fixture contact area is circular and radius of the contact area is much smaller compared to the radii of curvature of the two contacting bodies.
- The contact deformation is small and is independent of the contact pressure at other contact points.

Spherical locator and clamp contact surfaces are used in this work. The stiffness of the locators and clamps are assumed to be higher than the workpiece stiffness. Hertz's contact model is used to represent the elastic contact between spherical locators/clamps and planer workpiece surface. Some contact mechanics based solution approaches for optimal clamping and contact forces for minimum deformation are found in [Li and Melkote, 1999, Li *et al.*, 2000, Li and Melkote, 2001, Deng and Melkote, 2006], albeit these papers are concerned with fixture design only, without any integration with setup planning.

In the present module, the normal contact deformation  $\delta_n$  due to normal force  $P$  acting between a spherical-tipped fixture element and planer workpiece surface is obtained from Hertz's contact model [Johnson, 1985] as

$$\delta_n = \left[ \frac{9P^2}{16RE^2} \right]^{1/3} \quad (6.10)$$

and the normal load  $P_y$  to initiate yield in the workpiece material is given by the expression [Johnson, 1985]

$$P_y = \frac{\pi^3 R^2}{6E^2} (1.6Y)^3 \quad (6.11)$$

where  $1.6Y$  is the maximum contact pressure at workpiece-fixture interface according to von Mises' as well as Tresca' yield criteria. Here  $Y$  is the yield stress of the workpiece material in compression.

In Equations (6.10) and (6.11)

$$\frac{1}{R} = \frac{1}{R_w} + \frac{1}{R_f} \quad (6.12)$$

$$\frac{1}{E} = \frac{1-\nu_w^2}{E_w} + \frac{1-\nu_f^2}{E_f} \quad (6.13)$$

where  $R_w$  and  $R_f$  are the radii of curvature of the workpiece and fixture element contact surface,  $R$  is the equivalent radius of curvature of the two bodies in contact.  $E_w$  and  $E_f$  are the Young's moduli of elasticity of the workpiece and fixture element and  $E$  is the equivalent Young's modulus of elasticity; and  $\nu_w$  and  $\nu_f$  are the Poisson's ratios of the workpiece and fixture element respectively.

### 6.2.5 Locator and Clamp Design Module E

Module E calculates the proper size of the clamps and the locators. Size of a clamp depends on the magnitude of the machining force it has to experience and the tensile strength of the clamp material [Cecil, 2002]. For a screw clamp to apply a clamping force  $F_{\text{clamp}}$ , the clamp nominal diameter  $d_{\text{clamp}}$  can be found from the expression [Henriksen, 1973]:

$$d_{\text{clamp}} = \frac{T}{0.2 F_{\text{clamp}}} \quad (6.14)$$

where  $T$  is the torque applied at the head of the clamp screw. The minimum value of diameter of a screw clamp is found from the following relation [Mehta, 2004]:

$$\frac{T}{J} = \frac{2\tau}{d_{\text{clamp}}} \quad (6.15)$$

where  $J$  is the polar moment of inertia of the clamp screw,  $\tau$  is the allowable shear stress of the clamp material. Diameter  $d_{\text{clamp}}$  calculated from Equation (6.14) should be greater than  $d_{\text{clamp}}$  calculated from Equation (6.15).

Figure 6.4 shows the different parameters of a spherical locator. The relations among the different parameters of a spherical locator are given as [Henriksen, 1973]:

$$H = \frac{1}{3}D_L \text{ to } D_L \quad (6.16)$$

$$R_L = \frac{3}{2}D_L \quad (6.17)$$

$$l_L = L = \frac{3}{4}D_L \quad (6.18)$$

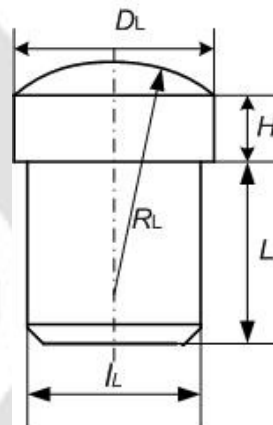


Figure 6.4. The parameters of a spherical locator

### 6.3 The Methodology for Generating Fixturing and Process Related Information

In this section, the fuzzy parameters are denoted with tilde ( $\sim$ ) as a diacritical mark. The overall functioning of the proposed system comprises the following steps: **Step 1:** Given the information on the part, machining operations, machines and tools as input to module A, the setup and machining operation sequences, datum for the setups are obtained. This module is described in detail in Chapter 3.

**Step 2:** Cutting tool parameters, depth of cut, feed rate and fuzzy specific cutting energy  $\tilde{u}_s$  for a machining operation are given as inputs to module B and the values of  $\tilde{F}_x, \tilde{F}_y$  and  $\tilde{F}_z$  are calculated.  $\tilde{u}_s$  varies with undeformed chip thickness  $t$  as follows [Shaw, 2005]:

$$\tilde{u}_s = \tilde{u}_0 t^{-\tilde{a}} \quad (6.19)$$

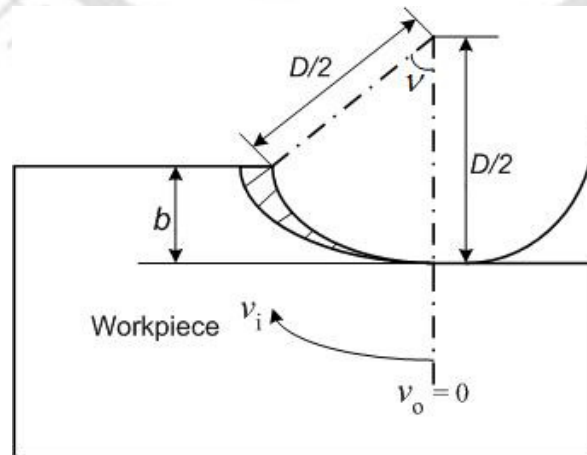
where  $\tilde{u}_0$  is the specific cutting energy at  $0^\circ$  tool rake angle and 0.25 mm undeformed chip thickness and  $\tilde{a}$  is a fuzzy index. The main cutting force in milling is the tangential force component  $F_t$  and it is expressed in terms of  $\tilde{u}_s$  as follows [Stephenson and Agapiou, 2005]:

$$\tilde{F}_t = \tilde{u}_s dt \quad (6.20)$$

where  $d$  is the depth of cut and  $t$  is the undeformed chip thickness.  $\tilde{F}_x, \tilde{F}_y$  and  $\tilde{F}_z$  can be calculated for different machining cases. As an example, the calculation for an end milling operation is done in the following manner. Undeformed chip thickness  $t$  is given by the expression [Stephenson and Agapiou, 2005]:

$$t = f \sin \nu \quad (6.21)$$

where  $f$  is feed per tooth of the cutter and  $\nu$  is the cutter engagement angle. Figure 6.5 shows the plan view for gradual engagement of the cutter during milling process. Here  $b$  is the radial depth of cut and  $D$  is the cutter diameter.



**Figure 6.5.** Cutter engagement angle  $\nu$  during milling process

The minimum value of  $\nu$  is  $0^\circ$ . The maximum value of the engagement angle can be found from Figure 6.5, as follows:

$$\cos \nu = \frac{D/2 - b}{D/2} \quad (6.22)$$

Simplifying Equation (6.22), the maximum value of the engagement angle  $\nu_m$  is found as

$$\nu_m = \cos^{-1} \left( 1 - \frac{2b}{D} \right) \quad (6.23)$$

Putting the expression of  $t$  from Equation (6.21) in Equation (6.20),  $F_t$  can be calculated as

$$\tilde{F}_t = \tilde{u}_s d f \sin \nu \quad (6.24)$$

The radial and axial force components  $F_r$  and  $F_a$  are found from  $F_t$  as [Stephenson and Agapiou, 2005]:

$$\tilde{F}_r = 0.3 \tilde{F}_t \quad (6.25)$$

$$\tilde{F}_a = \tilde{F}_r \tan \beta \quad (6.26)$$

where  $\beta$  is the helix angle of the cutter. Now Cartesian components  $\tilde{F}_x, \tilde{F}_y$  and  $\tilde{F}_z$  can be calculated in terms of  $\tilde{F}_t, \tilde{F}_r$  and  $\tilde{F}_a$  using Equations (6.1)–(6.3). The maximum value of  $\tilde{F}_x / \tilde{F}_y / \tilde{F}_z$  is set as the clamping force  $\tilde{F}_{\text{clamp}}$ .

Step 3:  $\tilde{F}_x, \tilde{F}_y, \tilde{F}_z, \tilde{F}_{\text{clamp}}$  and the part weight  $W$  are the inputs to module C for locator and clamp position optimization. Objective function and constraints are presented by Equations (6.7)–(6.9). If the feasible solution is not obtained,  $\tilde{F}_{\text{clamp}}$  is increased in steps of 5 % until a feasible solution is obtained.

Step 4: The value of  $\tilde{F}_{\text{clamp}}$  that provides the positive reaction forces at all locators is the required minimum  $\tilde{F}_{\text{clamp}}$ . A factor of safety of value 2 is chosen for  $\tilde{F}_{\text{clamp}}$  to take care of the uncertainties associated with dynamic effect of machining forces,

material removal effect and tool wear. The clamp diameter  $\tilde{d}_{\text{clamp}}$  is calculated from Equation (6.14) considering clamping torque  $\tilde{T}$  and  $\tilde{F}_{\text{clamp}}$  as fuzzy.

Step 5: In this work, a novel strategy is developed to find a range for the value of radius of curvature for the spherical clamp,  $\tilde{R}_{\text{clamp}}$ . In Equation (6.11),  $\tilde{R}, \tilde{Y}$  and  $\tilde{E}$  are fuzzy. As the workpiece surface is planer,  $\tilde{R} = \tilde{R}_f = \tilde{R}_{\text{clamp}}$ . The minimum value of the radius of curvature  $\tilde{R}_{\text{min}}$  is found from Equation (6.11) by replacing the normal load  $P_y$  with clamping force  $\tilde{F}_{\text{clamp}}$  and considering that  $\tilde{F}_{\text{clamp}}$  is within elastic limit.  $\tilde{R}_{\text{min}}$  is obtained from Equation (6.11) as

$$\tilde{R}_{\text{min}} = \sqrt{\frac{6\tilde{F}_{\text{clamp}}\tilde{E}^2}{(1.6\pi\tilde{Y})^3}} \quad (6.27)$$

To find the maximum value of the radius of curvature  $\tilde{R}_{\text{max}}$ , the following strategy is developed. Figure 6.6 shows the clamp parameters. Here  $r_{\text{clamp}}$  is the clamp radius,  $s$  is the height of the spherical clamp tip and  $R_{\text{clamp}}$  is the radius of curvature of the spherical clamp. From Figure 6.6,

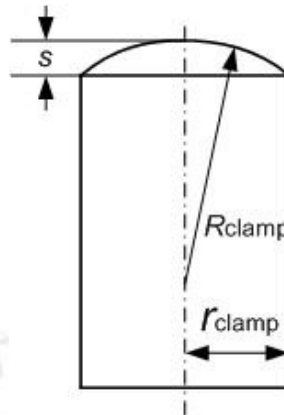
$$\tilde{R}_{\text{clamp}}^2 = (\tilde{R}_{\text{clamp}} - \tilde{s})^2 + r_{\text{clamp}}^2 \quad (6.28)$$

Neglecting very small terms, Equation (6.28) can be written as

$$\tilde{R}_{\text{clamp}} = \frac{r_{\text{clamp}}^2}{2\tilde{s}} \quad (6.29)$$

The contacting surface of the workpiece is considered to be a rough surface. With an objective of proper contact between the spherical clamp and workpiece,  $s$  must be equal to the peak to valley roughness height  $R_t$  of the workpiece surface. Hence, the maximum value of radius of curvature  $\tilde{R}_{\text{max}}$  is given by

$$\tilde{R}_{\text{max}} = \frac{\tilde{r}_{\text{clamp}}^2}{2\tilde{R}_t} \quad (6.30)$$



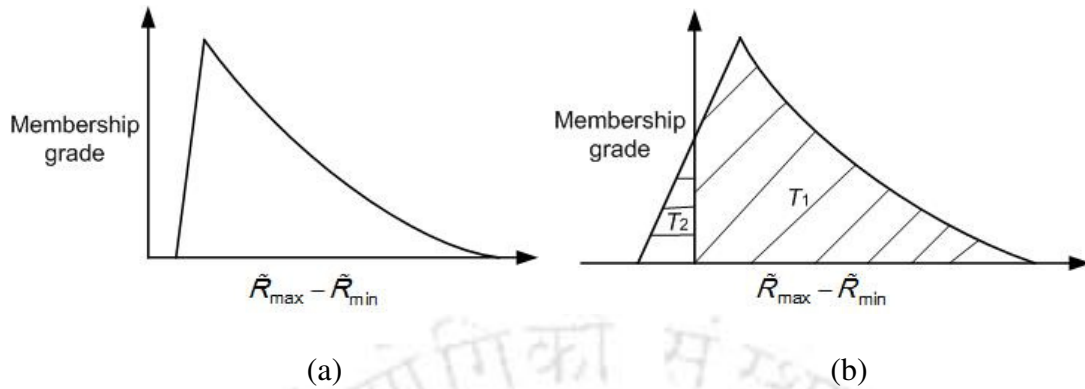
**Figure 6.6.** The parameters of a spherical clamp

Step 6: If  $\tilde{R}_{\min} < \tilde{R}_{\max}$ , design is proper. If  $\tilde{R}_{\min} > \tilde{R}_{\max}$ , there can be two options. Either the depth of cut/feed can be reduced so that machining forces are lower, or number of clamps can be increased to reduce  $\tilde{F}_{\text{clamp}}$  on each clamp. Decision has to be taken depending on the requirements and considering the pros and cons of both the options.

The maximum value of load at the onset of yielding  $\tilde{P}_y$  is checked considering planer clamp contact surface with the following relation [Chakrabarty, 1987]

$$\tilde{P}_y = \pi \tilde{r}_{\text{clamp}}^2 \tilde{Y} \left( 1 + \frac{\pi}{2} \right) \quad (6.31)$$

The value of  $\tilde{F}_{\text{clamp}}$  should always be lower than  $\tilde{P}_y$  calculated from Equation (6.31). Figure 6.7 shows a typical diagram for two possible cases of membership function of  $\tilde{R}_{\max} - \tilde{R}_{\min}$ . For case (a), all the values of  $\tilde{R}_{\max} - \tilde{R}_{\min}$  are positive and the design is proper for all membership grades. For case (b),  $\tilde{R}_{\max} - \tilde{R}_{\min}$  is a combination of positive and negative values and  $T1$  and  $T2$  are the positive and negative areas respectively. In this case, the ratio of the positive area  $T1$  to total area  $(T1+T2)$  indicates the possibility of the design being successful.



**Figure 6.7.** Membership function for  $\tilde{R}_{\max} - \tilde{R}_{\min}$

**Step 7:** The following strategy is developed to find the parameters of the locator. The deflection  $\delta$  of the locator on the primary datum under the part weight and other external forces is given by the relation

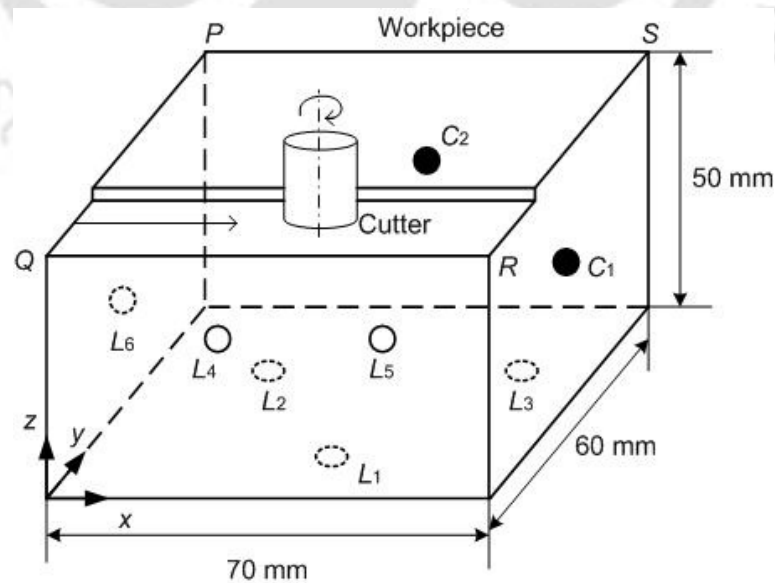
$$\delta = \frac{P_L l_L}{AE_L} \quad (6.32)$$

where  $P_L$  is the total load on the locator,  $l_L$  is the locator diameter,  $A$  is the cross-sectional area of the locator and  $E_L$  is the Young's modulus of elasticity of the locator material. Locator diameter ( $l_L$ ) is calculated by putting  $A = \pi l_L^2/4$  in Equation (6.32). Spherical locator button diameter  $D_L$  is calculated from Equation (6.18). Radius of curvature of the spherical locator button,  $R_L$  is found considering the onset of yielding in the workpiece material. Minimum radius of curvature is found from Equation (6.27) where  $F_{\text{clamp}}$  is replaced by the maximum locator reaction force. Maximum radius of curvature can be found using Equation (6.30) assuming proper contact between the workpiece and locators.

## 6.4 An Example End Milling Process

An end milling operation is used to machine the top face PQRS of the workpiece shown in Figure 6.8. From module A, primary datum for the setup is selected based on tolerance relation, surface area and surface quality. The largest face perpendicular to the primary datum is the secondary datum. The tertiary datum

is perpendicular to both the primary and secondary datum. The workpiece is a prismatic block of dimensions  $70 \times 60 \times 50 \text{ mm}^3$  and the workpiece material is AISI 1018 steel. Taking the density of AISI 1018 steel as  $7.87 \text{ gm/cc}$ , the weight of the workpiece is found to be  $16.5 \text{ N}$ . It is fixtured with three locators  $L_1$ ,  $L_2$  and  $L_3$  on the primary datum ( $x$ - $y$  plane), two locators  $L_4$  and  $L_5$  on the secondary datum ( $x$ - $z$  plane) and one locator  $L_6$  on the tertiary datum ( $y$ - $z$  plane). Clamp  $C_1$  is placed opposite to the locator on the tertiary datum and  $C_2$  is placed opposite to the locators on the secondary datum. Spherical locator and clamp contact surfaces are used in this work for proper contact with rough workpiece surface. Screw clamps made of 2340 medium carbon alloy steel are selected. Locator material is water hardening steel W1 with  $0.6 \%$  carbon content. Workpiece, clamp and locator material properties are given in Table 6.1. A  $20 \text{ mm}$  diameter helical end mill with four flutes and  $30^\circ$  helix angle is used for the milling operation. A torque of  $2000 \text{ N-mm}$  is applied at the head of the clamp screw with one hand operation [Rai and Xirouchakis, 2008]. The central line average (CLA) surface roughness height of the workpiece contact surface is considered as  $50 \mu\text{m}$  (N12). The entire tool path is discretized into 170 steps along  $x$  and  $y$ -axis for applying the computed machining forces.



**Figure 6.8.** The end milling of the example part

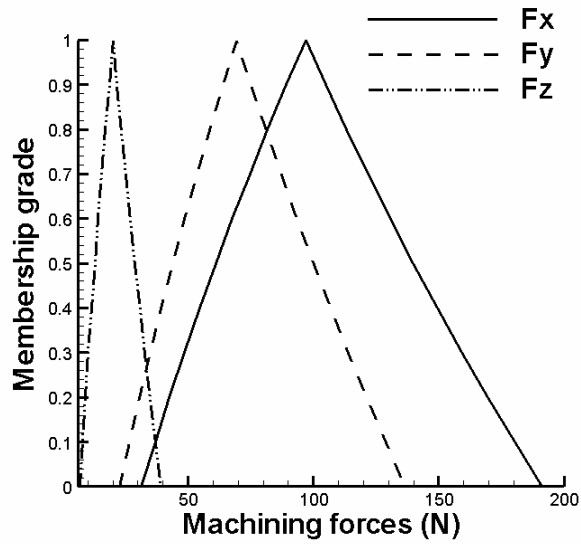
The specific cutting energy, yield stress and Young's modulus of elasticity of the workpiece material  $\tilde{u}_s$ ,  $\tilde{Y}$  and  $\tilde{E}_w$ , Young's modulus of elasticity of the clamp and locator materials  $\tilde{E}_c$  and  $\tilde{E}_L$ , clamping torque  $\tilde{T}$ , index  $\tilde{a}$  in Equation (6.19) and peak to valley roughness height of the workpiece contact surface  $\tilde{R}_t$  are treated as fuzzy numbers. The low ( $l$ ), most likely ( $m$ ) and high ( $h$ ) estimates of these parameters are given in Table 6.1. The basis of these estimates is that the variations in specific cutting energy and yield stress of the workpiece material may go up to  $\pm 30\%$  and  $\pm 10\%$  respectively. The Young's moduli of elasticity of the workpiece, clamp and locator materials may vary by  $\pm 5\%$ . The variations in clamping torque and peak to valley roughness height of the workpiece contact surface are considered as  $\pm 10\%$  and index  $a$  varies by  $\pm 20\%$ . Linear triangular fuzzy membership functions are assumed for these parameters. A linear triangular membership function is constructed by taking the membership grade as 1.0 at most likely ( $m$ ) and 0.5 at low ( $l$ ) and high ( $h$ ) estimates of a parameter. A typical triangular membership function is shown in Figure 4.1, Chapter 4

**Table 6.1.** The values of the fuzzy parameters

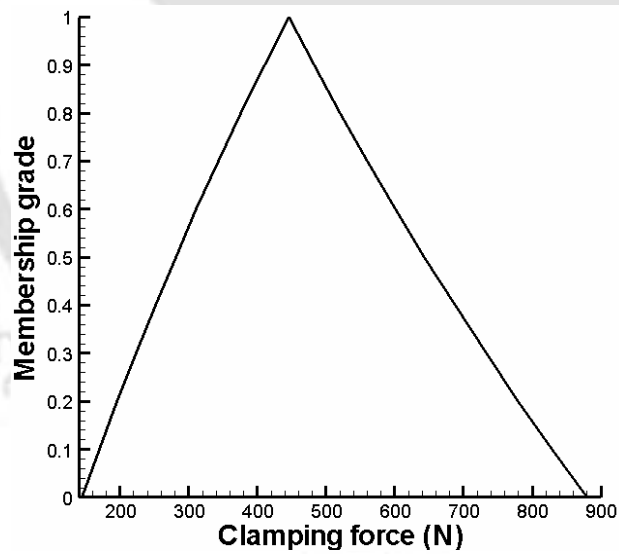
Parameters	Low ( $l$ )	Most likely ( $m$ )	High ( $h$ )
Specific cutting energy $\tilde{u}_s$ for AISI 1018 steel ( $\text{J}/\text{mm}^3$ )	1.8186	2.8856	4.1665
Index $\tilde{a}$	0.2	0.3	0.4
Yield stress $\tilde{Y}$ for AISI 1018 Steel ( $\text{N}/\text{mm}^2$ )	347.40	386	424.60
Young's modulus of elasticity $\tilde{E}_w$ for AISI 1018 Steel ( $\text{N}/\text{mm}^2$ )	190000	200000	210000
Young's modulus of elasticity $\tilde{E}_c$ for 2340 alloy Steel ( $\text{N}/\text{mm}^2$ )	190000	200000	210000
Young's modulus of elasticity $\tilde{E}_L$ for W1 water hardening Steel ( $\text{N}/\text{mm}^2$ )	190000	200000	210000
Clamping torque $\tilde{T}$ (N-mm)	1800	2000	2200
Peak to valley roughness height $\tilde{R}_t$ (mm)	0.200	0.225	0.250

The machining and clamping forces are considered as fuzzy numbers. Figure 6.9 shows the fuzzy machining forces  $F_x$ ,  $F_y$  and  $F_z$  and clamping force  $F_{\text{clamp}}$  at different membership grades for the end milling operation at 0.5 mm depth of cut and 0.1 mm/tooth feed. Standard 3-2-1 location with one clamp each on secondary and tertiary datum is followed in this case. From Figure 6.9 (a), the high ( $h$ ) estimates of  $F_x$ ,  $F_y$  and  $F_z$  at 0.5 membership grade are 139.89 N, 99.76 N and 28.50 N respectively. From Figure 6.9 (b), the most likely ( $m$ ) value of clamping force at membership grade 1.0 is 445.68 N and the low ( $l$ ) and high ( $h$ ) estimates at 0.5 membership grade are 280.88 N and 643.50 N respectively. Designing for the worst case condition, high estimate of clamping force 643.50 N at membership grade 0.5 is considered. Radius of the clamp  $r_{\text{clamp}}$  ( $d_{\text{clamp}}/2$ ) is found as 7 mm from Equation (6.14). The value of  $r_{\text{clamp}}$  is greater than the minimum value of  $r_{\text{clamp}}$  (4.82 mm) found from Equation (6.15). For finding the radius of curvature  $R_{\text{clamp}}$  for spherical clamp, minimum and maximum radius of curvature,  $R_{\text{min}}$  and  $R_{\text{max}}$  as obtained from Equations (6.27) and (6.30) are made equal. The value of  $R_{\text{clamp}}$  comes to be 98 mm at 0.5 mm depth of cut. Figure 6.10 shows the variation of machining forces  $F_x$ ,  $F_y$  and  $F_z$  with cutter engagement angle  $\nu$  for most likely ( $m$ ) value of machining forces at membership grade 1.0 for one revolution of the cutter.

Considering a very small deflection of 0.001 mm of the locator under the part weight and other external forces, locator diameter  $l_L$  is found as 12 mm from Equation (6.32). Spherical locator button diameter  $D_L$  is calculated as 16 mm from Equation (6.18). Radius of curvature of the spherical locator button,  $R_L$  comes to be 24 mm from Equation (6.17). However, in the proposed design,  $R_L$  is found considering the onset of yielding in the workpiece material. The minimum value of  $R_L$  is calculated as 87 mm from Equation (6.27) where  $F_{\text{clamp}}$  is replaced by the maximum locator reaction force 503.62 N for worst case machining and clamping forces. Height of the locator button,  $H$  and height of the locator,  $L$  are found as 8 mm and 12 mm respectively from Equations (6.16) and (6.18).  $H$  is considered half of the button diameter  $D_L$ .

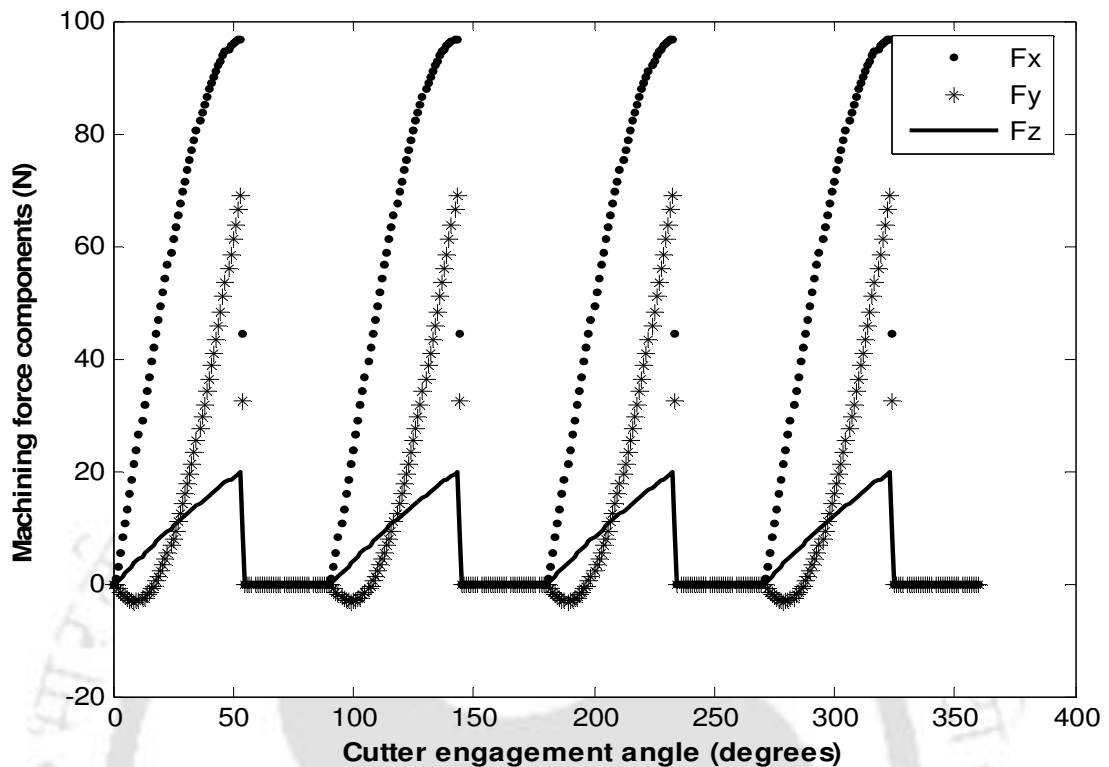


(a)



(b)

**Figure 6.9.** Membership function for (a) machining forces (b) clamping forces at 0.5 mm depth of cut and 0.1 mm/tooth feed



**Figure 6.10.** Variation of machining forces with cutter engagement angle at 0.5 mm depth of cut, 0.1 mm/tooth feed at membership grade 1.0

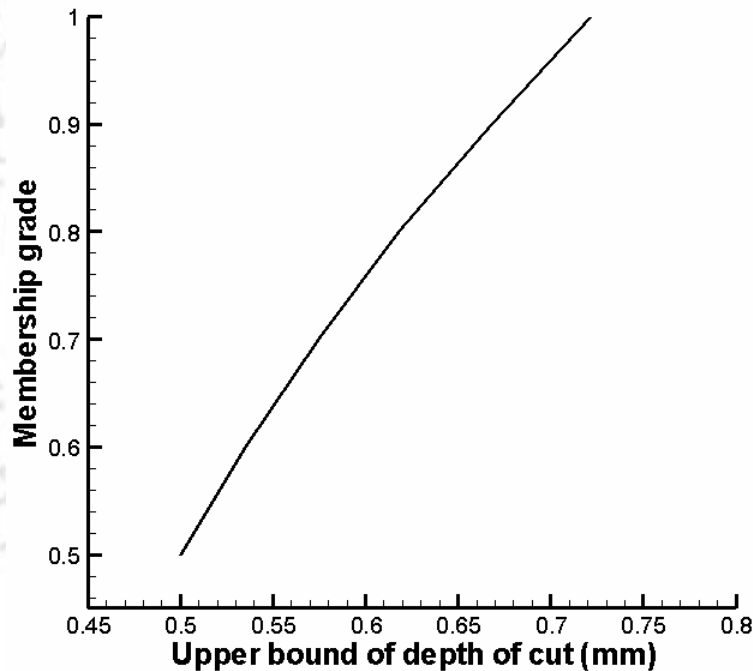
Figure 6.11 shows the upper bound of depth of cut at membership grades 0.5 and above for worst case design condition. High estimates of  $F_x$ ,  $F_y$ ,  $F_z$  and  $F_{clamp}$  at 0.5 membership grade are considered. Upper bound for depth of cut at 0.5 membership grade is 0.5 mm and at 1.0 membership grade, it is 0.722 mm.

Figure 6.12 shows the range of radius of curvature  $R_{max}-R_{min}$  and  $R_{min}$  for spherical clamp at 0.5 mm, 0.7 mm and 0.8 mm depths of cut. From Figure 6.12 (a), the ratio of positive area  $T1$  to total area ( $T1+T2$ ) is found as 0.9795, 0.9519 and 0.8575 for 0.5 mm, 0.7 mm and 0.8 mm depths of cut respectively. It indicates that there is 97.95 %, 95.19 % and 85.75 % possibility of the design being successful at 0.5 mm, 0.7 mm and 0.8 mm depths of cut. The extreme low and extreme high cases of machining and clamping forces are also considered for calculating the ratio of  $T1$  to ( $T1+T2$ ). It is observed that with increase in depth of cut, there is a greater chance of  $R_{max}-R_{min}$  being negative thus reducing the possibility of successful design. In this situation, the options are to either reduce the depth of cut/feed or to

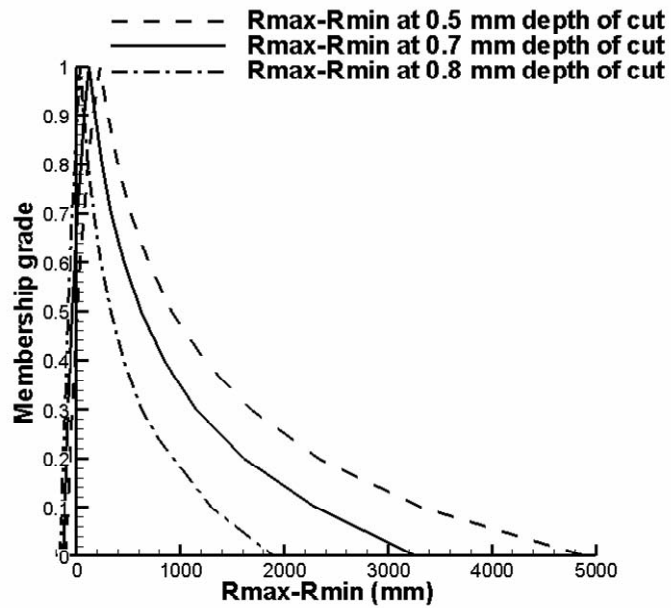
increase the number of clamps. The approximate relation between depth of cut  $d$ , feed  $f$  and cutting force  $F_c$  can be expressed by the following expression

$$F_c = k f d \quad (6.33)$$

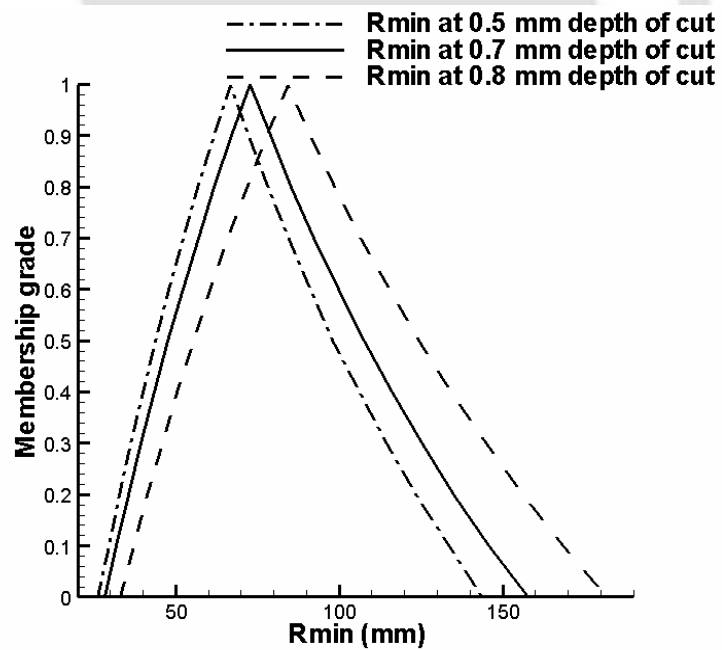
where  $k$  is the proportionality constant. Variable bounds for feed can be calculated using Equation (6.33) by the proposed method.



**Figure 6.11.** Membership function for upper bound of depth of cut for single clamp design



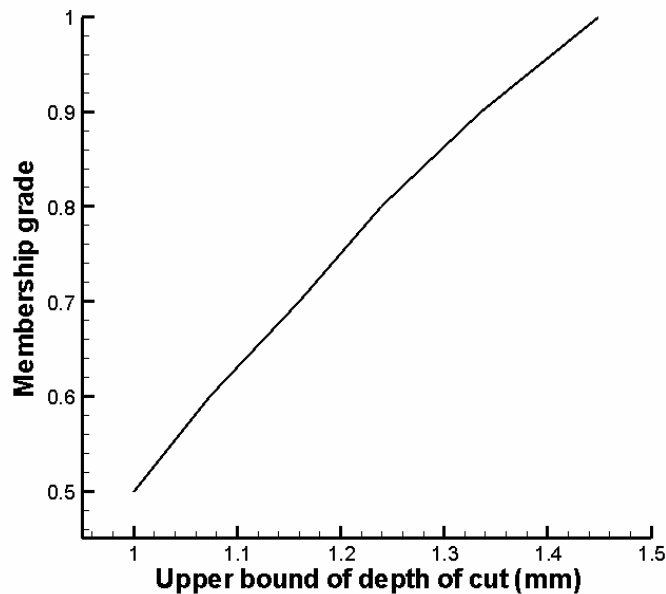
(a)



(b)

**Figure 6.12.** Membership function for (a)  $R_{max}-R_{min}$  (b)  $R_{min}$  for three different depths of cut

Machining and clamping forces increase with higher value of depth of cut and feed. To use higher value of depth of cut or feed, two clamps on one face may be used so that clamping force is reduced on each clamp. Figure 6.13 shows the upper bound of depth of cut at membership grades 0.5 and above for two clamp condition. High estimates of  $F_x$ ,  $F_y$ ,  $F_z$  and  $F_{\text{clamp}}$  at 0.5 membership grade are considered. Upper bound for depth of cut at 0.5 membership grade is 1 mm and at 1.0 membership grade, depth of cut can go upto 1.45 mm. Radius of the clamp  $r_{\text{clamp}}$  is found as 7 mm and minimum and maximum radius of curvature of the spherical clamp both are found to be 98 mm at 1 mm depth of cut. It is observed that the clamp parameters are same for both single clamp and double clamp design; only higher value of clamping force due to increased depth of cut is shared by two clamps.



**Figure 6.13.** Membership function for upper bound of depth of cut for two clamp design

The normal elastic deformation  $\delta_n$  at the clamp-workpiece and locator-workpiece contact surface are calculated from Equation (6.10) using worst case clamping force 643.50 N and highest locator reaction force 503.62 N. The values of

$\delta_n$  are found to be 0.006 mm and 0.005 mm at the clamp-workpiece and locator-workpiece interface which are quite small.

Optimized locator and clamp layout is found considering the worst case clamping force 643.50 N at 0.5 mm depth of cut and 0.1 mm feed/tooth of the cutter. Layout optimization is formed as a constrained optimization problem and solved using nonlinear optimization technique FMINCON in MATLAB (Version 7). FMINCON uses sequential quadratic programming (SQP) to find a constrained minimum of a scalar function of several variables. It starts at an initial estimate and solves a quadratic sub-problem at each iteration. The solution of the sub-problem is used to find the search direction for an optimal solution. The design variables in the optimization problem are the locator and clamp positions. Table 6.2 shows the feasible region for positioning the locators and clamps on the workpiece surfaces. The optimized locator and clamp positions for minimized maximum norm of the locator reactions are given in Table 6.3. It is observed that the optimized locator and clamp layout gives a much lower value of the norm of the locator reactions (657.55 N) than the value (1899.70 N) given by the initial locator and clamp layout.

**Table 6.2.** Feasible region for locators and clamps

Locator and clamp positions	Locator and clamp position constraints (mm)
$L_1 (x_1, y_1, z_1)$	$10 \leq x_1 \leq 60, 10 \leq y_1 \leq 50, z_1 = 0$
$L_2 (x_2, y_2, z_2)$	$10 \leq x_2 \leq 60, 10 \leq y_2 \leq 50, z_2 = 0$
$L_3 (x_3, y_3, z_3)$	$10 \leq x_3 \leq 60, 10 \leq y_3 \leq 50, z_3 = 0$
$L_4 (x_4, y_4, z_4)$	$10 \leq x_4 \leq 60, y_4 = 0, 10 \leq z_4 \leq 40$
$L_5 (x_5, y_5, z_5)$	$10 \leq x_5 \leq 60, y_5 = 0, 10 \leq z_5 \leq 40$
$L_6 (x_6, y_6, z_6)$	$x_6 = 0, 10 \leq y_6 \leq 50, 10 \leq z_6 \leq 40$
$C_1 (x_7, y_7, z_7)$	$x_7 = 70, 10 \leq y_7 \leq 50, 10 \leq z_7 \leq 40$
$C_2 (x_8, y_8, z_8)$	$10 \leq x_8 \leq 60, y_8 = 60, 10 \leq z_8 \leq 40$

**Table 6.3.** Optimized locator and clamp layout

Fixture elements	Initial locator and clamp layout ( $x, y, z$ ) (mm)	Optimized locator and clamp layout ( $x, y, z$ ) (mm)	Locator Reactions $R_i$ (N)
Locator $L_1$	(60, 30, 0)	(60, 18.12, 0)	0.73
Locator $L_2$	(45, 55, 0)	(60, 50, 0)	6.55
Locator $L_3$	(40, 35, 0)	(10, 10, 0)	37.72
Locator $L_4$	(10, 0, 10)	(10, 0, 26.65)	150.53
Locator $L_5$	(30, 0, 21)	(60, 0, 18.32)	393.22
Locator $L_6$	(0, 20, 22)	(0, 24.78, 19.60)	503.62
Clamp $C_1$	(70, 10, 20)	(70, 22.80, 25.82)	
Clamp $C_2$	(30, 60, 10)	(31.85, 60, 26.97)	

## 6.5 Summary

Consideration of fixturing constraints in setup planning is inevitable for generation of a feasible and robust setup plan. In this work a methodology is developed for incorporating fixturing requirements into the setup planning expert system described in Chapter 3. The uncertainties associated with the work material, clamp material and clamping torque are considered by means of fuzzy arithmetic. The proposed setup planning system provides inputs to fixture designer in terms of recommended depth of cut and feed, fuzzy clamping forces, approximate optimal locator and clamp layout and sizes of the locators and clamps. Locators and clamps are designed based on machining and clamping forces. A novel strategy for finding the radius of curvature of the spherical locators and clamps is proposed for proper contact with the workpiece surface. The fixture designer can further optimize the fixture plan by taking these inputs from the setup planning module. Machining force, clamping force, recommended cutting parameters, initial fixture layout and proper size of the clamp/locator for applying the required clamping forces are some of the important issues considered in detail in this work. The methodology is

explained with an example end milling process. The proposed methodology provides information to the fixture planner in order to enhance the feasibility of the fixture design. The information can be provided in offline as well as online mode. It is possible to integrate the proposed setup planning expert system with fixturing information generation module in a complete process planning system.





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## Illustrative Examples

The development phases of the setup planning expert system are described in detail in the Chapters 3–6. In this chapter, some example parts are presented in Section 7.1 and a summary is presented in Section 7.2.

### 7.1 Example Parts

In this section, some example parts are presented to demonstrate the application of the fuzzy set based setup planning methodology. Given the information about different features present in a part, machining operations, machine tools, cutting tools and material properties as input, the setup planning system automatically performs the tasks of setup formation, operation sequencing, datum selection, and generation of information related to fixturing. The proposed setup planning expert system has been implemented on a PC using the expert system shell CLIPS, an acronym for C Language Integrated Production System [Giarratano and Riley, 1998]. The detail of CLIPS is discussed in Section 3.3, Chapter 3. The machining is performed in a vertical machining center (MC) equipped with rotary index table and automatic tool changer (ATC) where various milling as well as drilling operations can be performed. The machining center contains simultaneously controlled three Cartesian axes X, Y, and Z. It is possible to machine five faces of a cubic workpiece in these types of machines in a single setup.

#### 7.1.1 Example Part 1

The features to be machined, their tool approach directions (TAD), and the corresponding machining operations for the Example Part 1 are shown in Figure 7.1. The raw stock is a prismatic block of dimensions  $70 \times 60 \times 50 \text{ mm}^3$  and the workpiece material is AISI 1018 steel. Taking the density of AISI 1018 steel as 7.87 gm/cc, the weight of the workpiece is found to be 16.5 N. Screw clamps are made of 2340

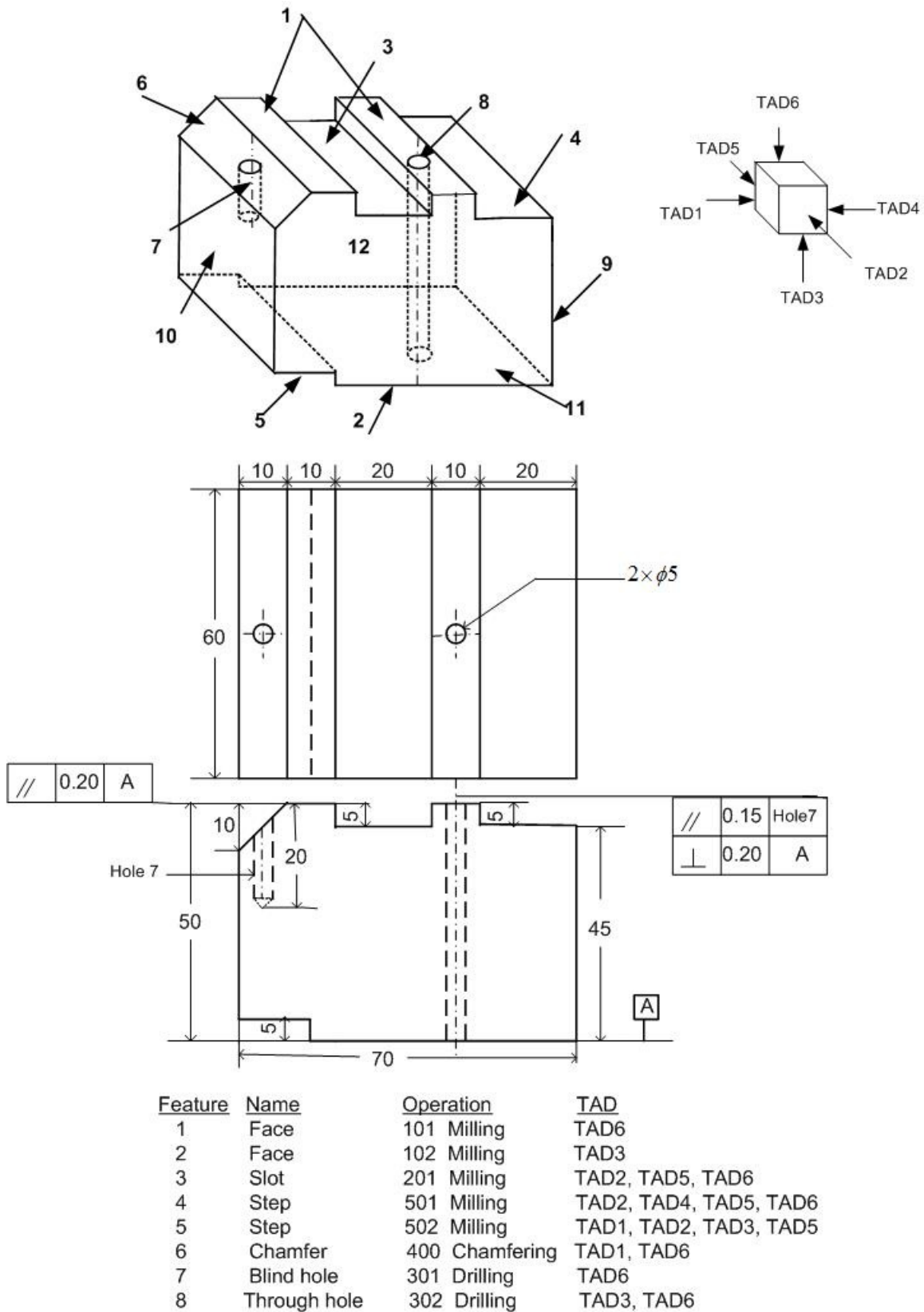


Figure 7.1. Example Part 1

medium carbon alloy steel and locator material is water hardening steel W1. It is assumed that all the six faces (faces 1, 2, 9, 10, 11, and 12) of the prismatic block are rough machined and only faces 1 and 2 (primary features for the other secondary features) are considered as machining features.

The through hole 8 has parallelism tolerance 0.15 mm with the blind hole 7 and perpendicularity tolerance 0.20 mm with face 2, so it has a tighter tolerance relation with 7. Face 1 has parallelism tolerance 0.20 mm with face 2. Face 2 also has positional tolerance relations with features 4, 5, and 6. Referring to Figure 7.1, the decision on whether to drill the through hole 8 first and then machine face 1 or the reverse is based on uncertain knowledge. There may be drilling burr formation, which mainly depends on ductility, tool geometry and feed rate. Therefore, the strategy developed for uncertainty management in the knowledge-base described in Section 4.3, Chapter 4 is adopted. The fuzzy input parameters ductility, tool geometry and feed rate are assigned fuzzy membership grades  $\mu_{\text{duc}}$ ,  $\mu_{\text{tool}}$  and  $\mu_{\text{feedrate}}$  as given in Table 4.1, Chapter 4. Overall membership grade for burr height in drilling is calculated using Equation (4.15), Chapter 4. A two flute high-speed steel conventional drill with 5 mm diameter ( $130^\circ$  point angle and  $30^\circ$  helix angle) is used for drilling hole 8, and feed rate is medium (200 mm/min) which gives the value of overall membership grade for burr height,  $\mu_c = 0.45$ . As the value of  $\mu_c$  is neither very low nor very high, the decision to drill hole 8 or machine face 1 first depends on the feedback received from the shop floor. Actual drilling process should be monitored on the shop floor to check for burr formation. This monitoring task is kept in the check list to be provided with the setup plan.

To deal with the uncertainty of selection of datum, the six enveloping faces of the Example Part 1 are considered. The main parameters considered for datum selection are tolerance relation with other features, surface area and surface quality as discussed in Section 4.3.2, Chapter 4. Face 2 has the maximum number of tolerance relations with other features. It has parallelism tolerance with feature 1, perpendicularity tolerance with feature 8, and positional tolerances with features 4, 5, and 6. It also has more surface area ( $70 \times 60 \text{ mm}^2$ ) compared to faces 9 and 10 ( $60 \times 50 \text{ mm}^2$  each), and 11 and 12 ( $70 \times 50 \text{ mm}^2$  each). The rules for selecting datum

roughness (Section 5.6, Chapter 5) suggest that, for attaining a parallelism tolerance 0.20 mm between faces 1 and 2, datum roughness should lie in the range 4.86–6  $\mu\text{m}$ . Table 7.1 shows the fuzzy membership grades assigned for the parameters for datum selection for the six faces of the Example Part 1. Using Equation (4.16), Chapter 4, the value of overall membership grade  $\mu_{\text{datum}}$  is calculated for all the faces. From Table 7.1, the maximum value of  $\mu_{\text{datum}}$  is 0.8 and the corresponding face 2 is selected as datum for machining the features 1, 3, 4, 6, 7, and 8 in one setup. This selection will ensure good tolerance, good surface area and good surface quality. Similarly, face 1 is selected as datum for machining the features 2, and 5. Moreover, one checklist for monitoring actual machining is provided with the suggested setup plan which is helpful in implementation of the adaptive learning strategy. It contains the conditions to be monitored on the shop floor, *e.g.* checking for burr height during drilling operation 302, and checking whether the parallelism tolerance 0.20 mm between faces 1 and 2 is achieved or not. If some deviations are detected, then the information is fed back to the process planner and the necessary modifications are made.

**Table 7.1.** Fuzzy membership grades for the parameters for datum selection

Faces	Good tolerance relation $\mu_{\text{gt}}$	Good surface area $\mu_{\text{gsa}}$	Good surface quality $\mu_{\text{gsq}}$	$\mu_{\text{datum}}$
1	0.7	0.8	0.8	0.7
2	0.9	0.8	0.8	0.8
9	0.4	0.6	0.5	0.4
10	0.5	0.6	0.5	0.5
11	0.2	0.7	0.5	0.2
12	0.2	0.7	0.5	0.2

The data file containing the information on the features, machining operations, machines and tools for the Example Part 1 is loaded into the CLIPS environment in module A along with the knowledge-based rules. The CLIPS files (with the extension .clp) for the knowledge-base of the expert system and facts of Example Part 1 are given in Appendix D. Module A generates the number of setups,

sequence of operations within a setup, datum for each setup along with the checklist. Next, cutting tool parameters, depth of cut, feed rate, and fuzzy specific cutting energy for different machining operations (to be performed on the features) are given as inputs to module B and the machining and clamping forces are calculated. Module C optimizes the fixture layout taking inputs from module B. Module D analyses the contact condition at the workpiece-fixture interface and module E designs the locators and clamps based on information obtained from modules B, C, and D. The features of Example Part 1 and their relevant information are given in Table 7.2.

**Table 7.2.** Feature information of Example Part 1

Feature	Type	Dimensions (mm)	Cutter	Cutter diameter D (mm)
1	Face	70×60	End mill	20
2	Face	70×60	End mill	20
3	Slot	20×5×60	End mill	20
4	Step	20×5×60	End mill	20
5	Step	15×5×60	End mill	20
6	Chamfer	45°×10×60	Chamfer mill	16
7	Blind hole	φ5×20	Drill	5
8	Through hole	φ5×50	Drill	5

When the expert system program is executed, the final setup plan is generated automatically. It contains the number of setups, sequence of operations within a setup, datum for each setup, machining and clamping forces and range of depths of cut/feed for each feature, approximate optimal fixture layout, and sizes of the locators and clamps along with the checklist. All these information for machining Example Part 1 are given in Tables 7.3–7.6. It requires two setups, Setup-1 and Setup-2 to machine the Example Part 1. Through hole 8 has two TADs and it is assigned TAD6 based on its tighter tolerance relation with feature 7. Features 3, 4, 5 and 6 have multiple TADs and they are assigned to TAD6 feature cluster where there is the maximum number of features. The machining and clamping forces given in Table 7.3 are the high estimates of forces at membership grade  $\mu=0.5$ , *i.e.* the

worst case condition forces.  $F_x$ ,  $F_y$  and  $F_z$  are forces in three Cartesian coordinate directions in milling, and  $F_{Th}$  and  $T_D$  are the thrust and torque in drilling. For milling, the machining forces are calculated for 0.1 mm/tooth feed and 30 m/min cutting speed. Ranges of depths of cut for milling operations are given in Table 7.3. For drilling, the machining forces are calculated for 2.5 mm depth of cut and 25 m/min cutting speed. Ranges of feeds for drilling operations are given in Table 7.3. The approximate relation between depth of cut  $d$ , feed  $f$ , and cutting force  $F_c$  can be expressed by the following expression:

$$F_c = k f d, \quad (7.1)$$

where  $k$  is the proportionality constant. Variable bounds for feed in case of milling, and depth of cut in case of drilling can be calculated using Eq. (7.1) by the proposed method. From Table 7.3, it is evident that for both the setups, maximum clamping force needed is 1285 N. If higher values of depth of cut/feed is used, two clamp design is to be adopted (Section 6.4, Chapter 6). However, with lower values of depth of cut/feed, standard 3-2-1 fixturing with one clamp on one face can be used. Locators and clamps are designed and fixture layout is optimized based on the maximum values of machining and clamping forces (279.35 N, 193.26 N, 56.35 N, and 1285 N). The procedure discussed in Section 6.3, Chapter 6 is followed to find locator and clamp sizes and optimized fixture layout. Table 7.4 presents the checklist given with the final setup plan. Tables 7.5 and 7.6 show optimized fixture layout for one clamp and two clamp fixturing system, and locator and clamp sizes for Example Part 1. Figure 7.2 shows the plan view for Example Part 1 with optimized fixture layout.

**Table 7.3.** Setup plan to machine the Example Part 1

Setups	Sequence of machining operations	Primary datum	Secondary datum	Tertiary datum	Machining forces/Torque (N/Nm)			Fclamp (N)	Depth of cut/ Feed rate (mm / mm/min)	
					$F_x$	$F_y$	$F_z$			
Setup-1	Operation 102 on feature 2 (Milling)	1	11/12	9/10	139.90	99.75	28.50	643.50	Upto 0.72 mm with one clamp on a face and upto 1.45 mm with two clamps on a face	
	Operation 502 on feature 5 (Milling)				279.35	193.26	56.35	1285	Upto 0.72 mm with one clamp on a face and upto 1.45 mm with two clamps on a face	
Setup-2	Operation 101 on feature 1 (Milling)	2	11/12	9/10	139.90	99.75	28.50	643.50	Upto 0.72 mm with one clamp on a face and upto 1.45 mm with two clamps on a face	
	Operation 501 on feature 4 (Milling)				279.35	193.26	56.35	1285	Upto 0.72 mm with one clamp on a face and upto 1.45 mm with two clamps on a face	
	Operation 201 on feature 3 (Milling)				279.35	193.26	56.35	1285	Upto 0.72 mm with one clamp on a face and upto 1.45 mm with two clamps on a face	
	Operation 301 on feature 7 (Drilling)				$F_{Th}$	$T_D$	349.80	0.98	804.55	136–200 mm/min
	Operation 302 on feature 8 (Drilling)				349.80	0.98	804.55	136–200 mm/min		
	Operation 400 on feature 6 (Chamfering)				$F_x$	$F_y$	$F_z$	210.46	69.30	36.65

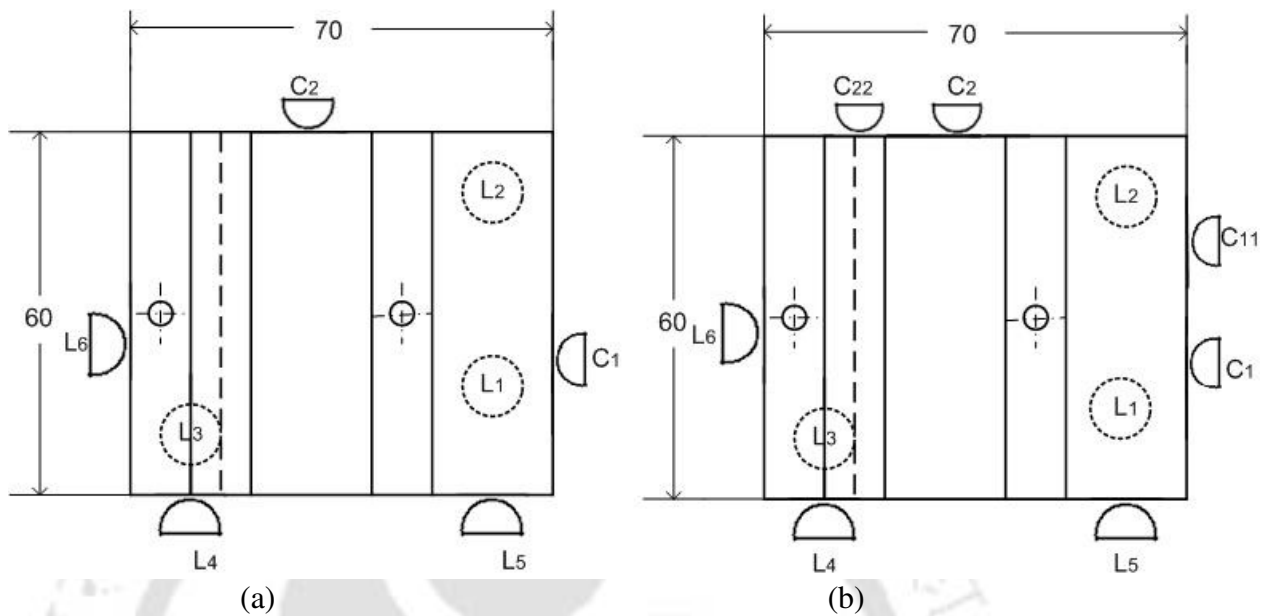
Table 7.4. The checklist given with the setup plan

Checklist
<p>(1) Check the burr height during drilling operation 302. If burr height <math>&lt;0.2</math> mm, milling face 1 precedes drilling hole 8. If burr height <math>&gt;0.2</math> mm, drilling hole 8 precedes milling face 1.</p> <p>(2) Check that the parallelism tolerance <math>0.20</math> mm between faces 1 and 2 is achieved. If the desired tolerance is not achieved with the ideal machining conditions, increase the datum roughness to a slightly higher value than <math>6 \mu\text{m}</math> and check tolerance. If the tolerance is still not achieved, then there is a need to check for the machine capability or some inherent error present in the machine.</p>

Table 7.5. Optimized fixture layout with one clamp on one face for Setup-1 and Setup-2

Fixture elements	Initial fixture layout	Optimized fixture layout
	$(x, y, z)$ (mm)	$(x, y, z)$ (mm)
Locator $L_1$	(60, 30, 0)	(60, 18.12, 0)
Locator $L_2$	(45, 55, 0)	(60, 50, 0)
Locator $L_3$	(40, 35, 0)	(10, 10, 0)
Locator $L_4$	(10, 0, 10)	(10, 0, 26.65)
Locator $L_5$	(30, 0, 21)	(60, 0, 18.32)
Locator $L_6$	(0, 20, 22)	(0, 24.78, 19.60)
Clamp $C_1$	(70, 10, 20)	(70, 22.80, 25.82)
Clamp $C_2$	(30, 60, 10)	(31.85, 60, 26.97)

Locator and clamp sizes
Radius of the clamp, $r_{\text{clamp}} = 7$ mm
Radius of curvature of clamp, $R_{\text{clamp}} = 98$ mm
Radius of curvature of the locator button, $R_L = 87$ mm
Locator diameter, $l_L = 12$ mm
Spherical locator button diameter, $D_L = 16$ mm
Height of the locator button, $H = 8$ mm
Height of the locator, $L = 12$ mm



**Figure 7.2.** Plan view for Example Part 1 with optimized fixture layout with (a) one clamp on one face (b) two clamps on one face

**Table 7.6.** Optimized fixture layout with two clamps on one face for Setup-1 and Setup-2, and fixture element sizes

Fixture elements	Initial fixture layout	Optimized fixture layout
	(x, y, z) (mm)	(x, y, z) (mm)
Locator $L_1$	(60, 30, 0)	(59.20, 15.55, 0)
Locator $L_2$	(45, 55, 0)	(60, 50, 0)
Locator $L_3$	(40, 35, 0)	(10, 10, 0)
Locator $L_4$	(10, 0, 10)	(10, 0, 22.65)
Locator $L_5$	(30, 0, 21)	(60, 0, 14.52)
Locator $L_6$	(0, 20, 22)	(0, 26.53, 20.40)
Clamp $C_1$	(70, 10, 20)	(70, 22.80, 25.82)
Clamp $C_{11}$	(70, 40, 30)	(70, 40, 24.95)
Clamp $C_2$	(30, 60, 10)	(30, 60, 14.30)
Clamp $C_{22}$	(10, 60, 20)	(18.55, 60, 17.38)

### 7.1.2 Example Part 2

The features to be machined, their TADs, and the corresponding machining operations for the Example Part 2 (part taken from Liu and Wang, 2007) are shown in Figure 7.3. The raw stock is a prismatic block of dimensions 200×100×50 mm<sup>3</sup> and the workpiece material is cast iron. Taking the density of cast iron as 7.2 gm/cc, the weight of the workpiece is found to be 72 N. Screw clamps are made of 2340 medium carbon alloy steel and locator material is water hardening steel W1. It is assumed that all the six faces of the prismatic block are rough machined and only faces F1 and F2 are considered as machining features. The part contains fourteen machining features including the faces F1 and F2.

As the workpiece material is brittle (made of cast iron), chance of burr formation is low. Overall membership grade for burr heights in drilling holes F7, F9, F11, F12, F13, and F14 are calculated using Equation (4.15), Chapter 4. A two flute high-speed steel conventional drill with 5 mm diameter (118° point angle and 30° helix angle) is used for drilling the holes, and feed rate is medium (200 mm/min) which gives the value of overall membership grade for burr height,  $\mu_c = 0.14$ . As the value of  $\mu_c$  is very low, machining the face F2 can be done prior to drilling the holes.

Following the procedure for selection of datum discussed in Section 4.3.2, Chapter 4, Face F1 is selected as datum for machining the features F2, F4, F5, F6, F8, and F10 in one setup, and Face F2 is selected as datum for machining the features F1, and F3 in another setup. Face F2 has parallelism tolerance 0.02 mm with face F1. The rules for selecting datum roughness (Section 5.6, Chapter 5) suggest that, for attaining a parallelism tolerance 0.02 mm between faces F1 and F2, datum roughness should lie in the range 5.43–6  $\mu\text{m}$ . The checklist contains the conditions to be monitored on the shop floor, *e.g.* checking whether the desired parallelism tolerance 0.02 mm between faces F1 and F2 are achieved or not. The features of Example Part 2 and their relevant information are given in Table 7.7.

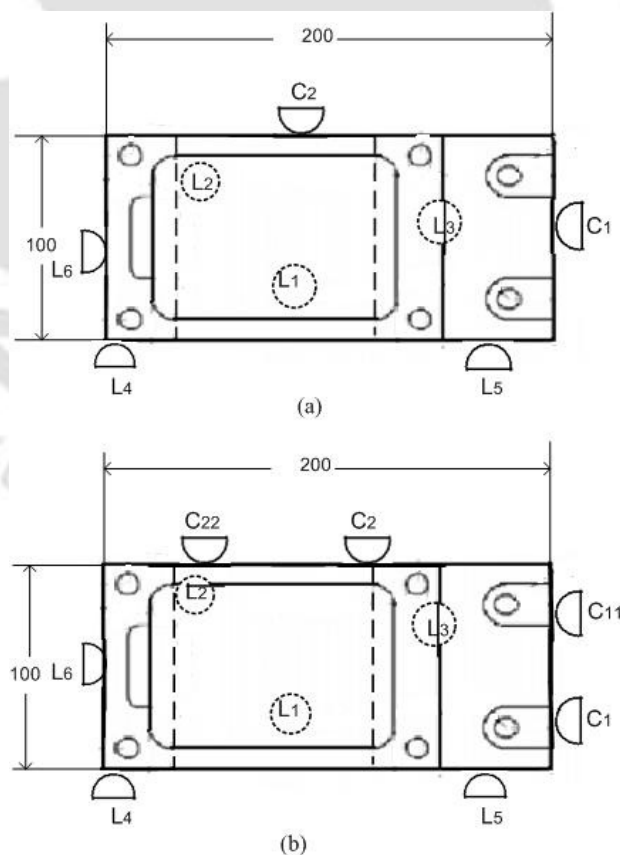


**Table 7.7.** Feature information of Example Part 2

Feature	Type	Dimensions (mm)	Cutter	Cutter diameter D (mm)
F1	Face	200×100	End mill	20
F2	Face	200×100	End mill	20
F3	Slot	100×90×10	End mill	20
F4	3-side pocket	40×10×10	End mill	10
F5	Step	100×50×30	End mill	20
F6	Slot	25×20×10	End mill	10
F7	Through hole	φ5×20	Drill	5
F8	Slot	25×20×10	End mill	10
F9	Through hole	φ5×20	Drill	5
F10	Pocket	110×80×20	End mill	20
F11	Through hole	φ5×50	Drill	5
F12	Through hole	φ5×50	Drill	5
F13	Through hole	φ5×50	Drill	5
F14	Through hole	φ5×50	Drill	5

After execution of the expert system program, the final setup plan is generated. Tables 7.8–7.13 presents all the setup planning information for machining Example Part 2. It requires two setups, Setup-1 and Setup-2 to machine the Example Part 2. Through holes F7, F9, F11, F12, F13, and F14 have two TADs (TAD3 and TAD6) each and they are assigned TAD6 feature cluster where there is the maximum number of features. Features F5, F6 and F8 also have two TADs (TAD2 and TAD6) and they are assigned to TAD6 feature cluster where there is the maximum number of features. For milling, the machining forces are calculated for 0.1 mm/tooth feed and 18 m/min cutting speed and for drilling, the machining forces are calculated for 2.5 mm depth of cut and 25 m/min cutting speed. While machining the pocket F10 (Figure 7.3) the milling force increases at the four corners of the pocket than at the straight walls. This is because the portion of the circumference of the tool engaged with the work material is more (approximately 2 times) at the corners than at the straight walls [Kramer, 1991]. The higher value of the milling force at the corners of the pocket F10 is incorporated in Table 7.8. From Table 7.8, it is evident that for

Setup-1, maximum clamping force needed is 642.52 N, and for Setup-2, maximum clamping force needed is 1285 N. If higher values of depth of cut/feed is used, two clamp design is to be adopted (Section 6.4, Chapter 6). However, with lower values of depth of cut/feed, standard 3-2-1 fixturing with one clamp on one face can be used. Range of depth of cut/feed for one clamp and two clamp fixturing are given in Table 7.8. The procedure discussed in Section 6.3, Chapter 6 is followed to find locator and clamp sizes and optimized fixture layout. Fixture layout for each setup is optimized based on the maximum values of machining and clamping forces for the setup. Table 7.9 presents the checklist given with the final setup plan. Tables 7.10 and 7.11 show optimized fixture layout for Setup-1 for one clamp and two clamp fixturing system and Tables 7.12 and 7.13 show optimized fixture layout for Setup-2 for one clamp and two clamp fixturing system, and fixture element sizes for Example Part 2. Figure 7.4 shows the plan view for Example Part 2 with optimized fixture layout for Setup-2.



**Figure 7.4.** Plan view for Example Part 2 with optimized fixture layout with (a) one clamp on one face (b) two clamps on one face

**Table 7.8.** Setup plan to machine the Example Part 2

Setups	Sequence of machining operations	Primary datum	Secondary datum	Tertiary datum	Machining forces/Torque (N/Nm)			Fclamp (N)	Depth of cut/ Feed rate (mm, mm/min)
					$F_x$	$F_y$	$F_z$		
Setup-1	Operation 101 on feature F1 (Milling)	F2	F15/F16	F17	97.87	68.95	19.86	450.25	Upto 1.02 mm with one clamp on a face and upto 2.05 mm with two clamps on a face
	Operation 201 on feature F3 (Milling)				139.68	96.63	28.18	642.52	Upto 0.72 mm with one clamp on a face and upto 1.443 mm with two clamps on a face
Setup-2	Operation 102 on feature F2 (Milling)	F1	F15/F16	F17	$F_x$	$F_y$	$F_z$	450.25	Upto 1.02 mm with one clamp on a face and upto 2.05 mm with two clamps on a face
	Operation 501 on feature F5 (Milling)				97.87	68.95	19.86	642.52	Upto 0.72 mm with one clamp on a face and upto 1.443 mm with two clamps on a face
	Operation 402 on feature F10 (Milling)				139.68	96.63	28.18	1285	Upto 0.72 mm with one clamp on a face and upto 1.45 mm with two clamps on a face
	Operation 401 on feature F4 (Milling)				279.35	193.26	56.35	818.00	Upto 0.71 mm with one clamp on a face and upto 1.485 mm with two clamps on a face
	Operation 202 on feature F6 (Milling)				139.75	177.82	34.80	818.00	Upto 0.71 mm with one clamp on a face and upto 1.485 mm with two clamps on a face
	Operation 203 on feature F8 (Milling)				139.75	177.82	34.80	818.00	Upto 0.71 mm with one clamp on a face and upto 1.485 mm with two clamps on a face
	Operation 304 on feature F12 (Drilling)				$F_{Tn}$	$T_D$	693.65	152–200 mm/min	
	Operation 303 on feature F11 (Drilling)				301.60	0.96	693.65	152–200 mm/min	
	Operation 306 on feature F14 (Drilling)				301.60	0.96	693.65	152–200 mm/min	
	Operation 305 on feature F13 (Drilling)				301.60	0.96	693.65	152–200 mm/min	
	Operation 301 on feature F7 (Drilling)				301.60	0.96	693.65	152–200 mm/min	
	Operation 302 on feature F9 (Drilling)				301.60	0.96	693.65	152–200 mm/min	

**Table 7.9.** The checklist given with the setup plan

Checklist
Check that the parallelism tolerance 0.02 mm between faces F1 and F2 is achieved. If the desired tolerance is not achieved with the ideal machining conditions, increase the datum roughness to a slightly higher value than 6 $\mu\text{m}$ and check tolerance. If the tolerance is still not achieved, then there is a need to check for the machine capability or some inherent error present in the machine.

**Table 7.10.** Optimized fixture layout with one clamp on one face for Setup-1

Fixture elements	Initial fixture layout	Optimized fixture layout
	(x, y, z) (mm)	(x, y, z) (mm)
Locator $L_1$	(100, 30, 0)	(90.65, 31.70, 0)
Locator $L_2$	(50, 70, 0)	(10, 85.65, 0)
Locator $L_3$	(150, 60, 0)	(180, 88.25, 0)
Locator $L_4$	(70, 0, 30)	(10, 0, 35.50)
Locator $L_5$	(120, 0, 40)	(180, 0, 14)
Locator $L_6$	(0, 50, 25)	(0, 44.32, 23.25)
Clamp $C_1$	(200, 50, 25)	(200, 59, 27.28)
Clamp $C_2$	(110, 100, 30)	(99.88, 100, 25.72)

**Table 7.11.** Optimized fixture layout with two clamps on one face for Setup-1

Fixture elements	Initial fixture layout	Optimized fixture layout
	(x, y, z) (mm)	(x, y, z) (mm)
Locator $L_1$	(100, 30, 0)	(99.92, 20.73, 0)
Locator $L_2$	(50, 70, 0)	(20.75, 76, 0)
Locator $L_3$	(150, 60, 0)	(180, 63.87, 0)
Locator $L_4$	(70, 0, 30)	(10, 0, 38.80)
Locator $L_5$	(120, 0, 40)	(180, 0, 19.54)
Locator $L_6$	(0, 50, 25)	(0, 28.55, 24.78)
Clamp $C_1$	(200, 30, 25)	(200, 46.68, 25.14)
Clamp $C_{11}$	(200, 70, 30)	(200, 70, 36.82)
Clamp $C_2$	(110, 100, 30)	(110, 100, 30.15)
Clamp $C_{22}$	(60, 100, 20)	(53, 100, 26.82)

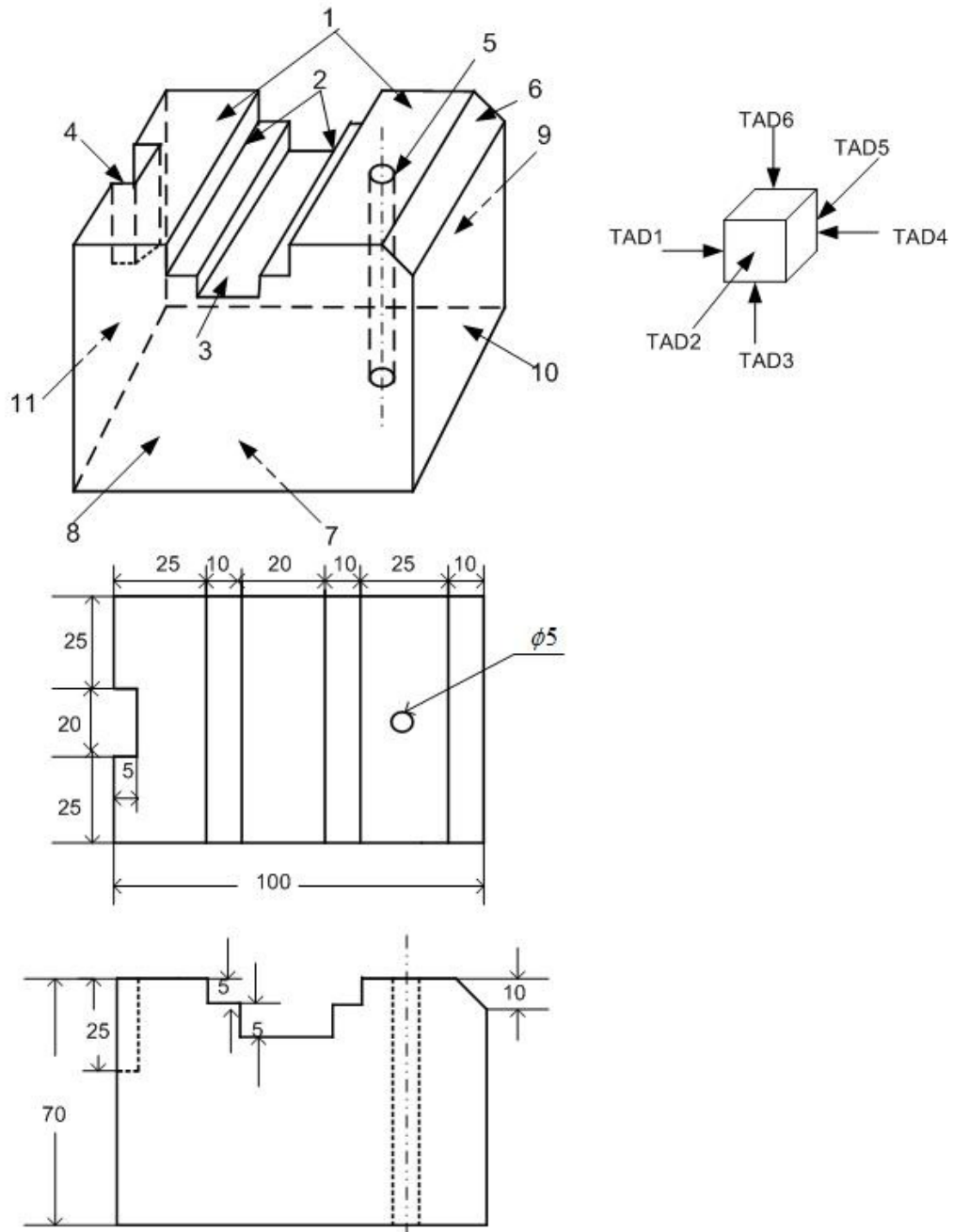
**Table 7.12.** Optimized fixture layout with one clamp on one face for Setup-2

Fixture elements	Initial fixture layout	Optimized fixture layout
	(x, y, z) (mm)	(x, y, z) (mm)
Locator $L_1$	(100, 30, 0)	(99.50, 25, 0)
Locator $L_2$	(50, 70, 0)	(49.55, 72.80, 0)
Locator $L_3$	(150, 60, 0)	(151, 62.78, 0)
Locator $L_4$	(70, 0, 30)	(10, 0, 37.55)
Locator $L_5$	(120, 0, 40)	(180, 0, 28.80)
Locator $L_6$	(0, 50, 25)	(0, 41.72, 24.80)
Clamp $C_1$	(200, 50, 25)	(200, 60, 25.23)
Clamp $C_2$	(110, 100, 30)	(100, 100, 34.66)

**Table 7.13.** Optimized fixture layout with two clamps on one face for Setup-2, and fixture element sizes

Fixture elements	Initial fixture layout	Optimized fixture layout
	(x, y, z) (mm)	(x, y, z) (mm)
Locator $L_1$	(100, 30, 0)	(98.15, 11.65, 0)
Locator $L_2$	(50, 70, 0)	(50, 79.25, 0)
Locator $L_3$	(150, 60, 0)	(152.25, 70.54, 0)
Locator $L_4$	(70, 0, 30)	(10, 0, 40)
Locator $L_5$	(120, 0, 40)	(180, 0, 12.10)
Locator $L_6$	(0, 50, 25)	(0, 48.17, 21.66)
Clamp $C_1$	(200, 30, 25)	(200, 31, 27)
Clamp $C_{11}$	(200, 70, 30)	(200, 70, 35.55)
Clamp $C_2$	(110, 100, 30)	(110, 100, 32)
Clamp $C_{22}$	(60, 100, 20)	(58.90, 100, 25.55)
Locator and clamp sizes		
Radius of the clamp, $r_{\text{clamp}} = 10.5$ mm		
Radius of curvature of clamp, $R_{\text{clamp}} = 227$ mm		
Radius of curvature of the locator button, $R_L = 172$ mm		
Locator diameter, $l_L = 12$ mm		
Spherical locator button diameter, $D_L = 16$ mm		
Height of the locator button, $H = 8$ mm		
Height of the locator, $L = 12$ mm		





<u>Feature</u>	<u>Name</u>	<u>Operation</u>	<u>TAD</u>
1	Face	101 Milling	TAD6
2	Slot	201 Milling	TAD2, TAD5, TAD6
3	Slot	202 Milling	TAD2, TAD5, TAD6
4	Slot	203 Milling	TAD1
5	Through hole	301 Drilling	TAD3, TAD6
6	Chamfer	401 Chamfering	TAD4, TAD6

**Figure 7.5.** Example Part 3

of overall membership grade for burr height,  $\mu_c = 0.14$ . As the value of  $\mu_c$  is very low, machining the Face 1 can be done prior to drilling hole 5.

Following the procedure for selection of datum discussed in Section 4.3.2, Chapter 4, face 7 is selected as datum for machining the features 1, 2, 3, 4, 5, and 6. The features of Example Part 3 and their relevant information are given in Table 7.14.

**Table 7.14.** Feature information of Example Part 3

Feature	Type	Dimensions (mm)	Cutter	Cutter diameter D (mm)
1	Face	100×70	End mill	20
2	Slot	70×40×5	End mill	20
3	Slot	70×20×5	End mill	20
4	Slot	25×20×5	End mill	10
5	Through hole	$\phi 5 \times 70$	Drill	5
6	Chamfer	45°×10×70	Chamfer mill	16

After execution of the expert system program, the final setup plan is generated. Tables 7.15–7.18 presents all the setup planning information for machining Example Part 3. It requires one setup, Setup-1 to machine the Example Part 3. The slots 2 and 3, through hole 5, and chamfer 6 have multiple TADs each (as shown in Figure 7.5) and they are assigned TAD6 feature cluster where there is the maximum number of features. For milling, the machining forces are calculated for 0.1 mm/tooth feed and 18 m/min cutting speed and for drilling, the machining forces are calculated for 2.5 mm depth of cut and 25 m/min cutting speed. From Table 7.15, it is evident that for Setup-1, maximum clamping force needed is 818 N. Range of depth of cut/feed for one clamp and two clamp fixturing are given in Table 7.15. The procedure discussed in Section 6.3, Chapter 6 is followed to find locator and clamp sizes and optimized fixture layout. Fixture layout is optimized based on the maximum values of machining and clamping forces for the setup. Tables 7.16 and 7.17 show optimized fixture layout for the Example Part 3 for one clamp and two clamp fixturing system, and Table 7.18 shows the fixture element sizes. Figure 7.6 shows the plan view for Example Part 3 with optimized fixture layout.

**Table 7.15.** Setup plan to machine the Example Part 3

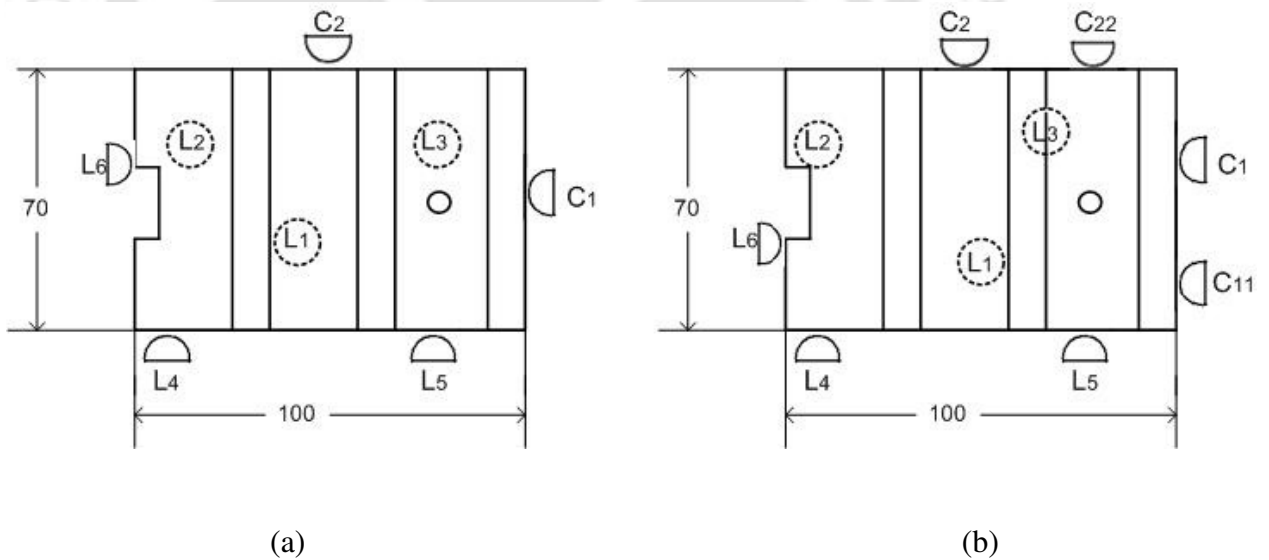
Setups	Sequence of machining operations	Primary datum	Secondary datum	Tertiary datum	Machining forces/Torque (N/Nm)	Fclamp (N)	Depth of cut/ Feed rate (mm / mm/min)
Setup-1	Operation 101 on feature 1 (Milling)	7	8/9	10	$F_x$ $F_y$ $F_z$ 97.87 68.95 19.86	450.25	Upto 1.02 mm with one clamp on a face and upto 2.05 mm with two clamps on a face
	Operation 201 on feature 2 (Milling)				139.68 96.63 28.18	642.52	Upto 0.72 mm with one clamp on a face and upto 1.443 mm with two clamps on a face
	Operation 202 on feature 3 (Milling)				139.68 96.63 28.18	642.52	Upto 0.72 mm with one clamp on a face and upto 1.443 mm with two clamps on a face
	Operation 203 on feature 4 (Milling)				139.75 177.82 34.80	818.00	Upto 0.71 mm with one clamp on a face and upto 1.485 mm with two clamps on a face
	Operation 401 on feature 6 (Chamfering)				140 121.55 30.58	643.55	Upto 0.722 mm with one clamp on a face and upto 1.445 mm with two clamps on a face
	Operation 301 on feature 5 (Drilling)				$F_{Th}$ $T_D$ 301.60 0.96	693.65	152–200

**Table 7.16.** Optimized fixture layout with one clamp on one face for Example Part 3

Fixture elements	Initial fixture layout	Optimized fixture layout
	(x, y, z) (mm)	(x, y, z) (mm)
Locator $L_1$	(50, 30, 0)	(42.78, 29, 0)
Locator $L_2$	(25, 50, 0)	(12.65, 50.44, 0)
Locator $L_3$	(60, 50, 0)	(79.65, 64.65, 0)
Locator $L_4$	(30, 0, 30)	(10, 0, 37.30)
Locator $L_5$	(70, 0, 40)	(80, 0, 22)
Locator $L_6$	(0, 40, 25)	(0, 38.73, 21.86)
Clamp $C_1$	(100, 30, 25)	(100, 31.54, 28.78)
Clamp $C_2$	(50, 750, 30)	(48.45, 75, 33.18)

**Table 7.17.** Optimized fixture layout with two clamps on one face for Example Part 3

Fixture elements	Initial fixture layout	Optimized fixture layout
	(x, y, z) (mm)	(x, y, z) (mm)
Locator $L_1$	(50, 30, 0)	(56.63, 24.35, 0)
Locator $L_2$	(25, 50, 0)	(10, 51.26, 0)
Locator $L_3$	(60, 50, 0)	(68.45, 56.60, 0)
Locator $L_4$	(30, 0, 30)	(10, 0, 36.15)
Locator $L_5$	(70, 0, 40)	(80, 0, 21.58)
Locator $L_6$	(0, 40, 25)	(0, 26.65, 22.28)
Clamp $C_1$	(100, 30, 25)	(100, 38, 26.64)
Clamp $C_{11}$	(100, 40, 30)	(100, 40, 37.85)
Clamp $C_2$	(50, 750, 30)	(50, 75, 31.64)
Clamp $C_{22}$	(75, 75, 20)	(66.95, 75, 27.85)



**Figure 7.6.** Plan view for Example Part 3 with optimized fixture layout with (a) one clamp on one face (b) two clamps on one face

**Table 7.18.** Sizes of the locators and clamps to be used for Example Part 3

Locator and clamp sizes
Radius of the clamp, $r_{\text{clamp}} = 10.5$ mm
Radius of curvature of clamp, $R_{\text{clamp}} = 227$ mm
Radius of curvature of the locator button, $R_L = 172$ mm
Locator diameter, $l_L = 12$ mm
Spherical locator button diameter, $D_L = 16$ mm
Height of the locator button, $H = 8$ mm
Height of the locator, $L = 12$ mm

## 7.2 Summary

In this chapter, three example parts are presented to demonstrate the application of the fuzzy set based setup planning methodology. The input to the setup planning system is the information about different features present in a part, machining operations, machine tools, cutting tools and material properties, and the output is the setup plan to machine the part which comprises the number of setups, machining operation sequences within a setup, datum for each setup, fuzzy machining and clamping forces for each feature, range of depth of cut/feed for machining the features, near optimal fixture layout, and sizes of the locators and clamps. Thus, the developed setup planning system provides additional information on machining and clamping forces, cutting parameters, and fixturing in addition to normal setup planning information.

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## Conclusions and Scope for Future Work

The previous chapters have presented the background, the methodologies developed for setup planning of prismatic parts and the results in detail as part of this research work. The present chapter concludes the thesis by summarising the important conclusions, identifying the main research contributions and by exploring the scope for future research directions.

### 8.1 Conclusions

The objectives of the present thesis is to develop a fuzzy set based setup planning expert system considering fixturing aspects with the capability of adaptive learning and uncertainty management. The benefits of using expert system for setup planning and fuzzy sets to deal with the uncertainties associated with setup planning knowledge is explored. An adaptive learning strategy is adopted so that the setup planning system is able to learn from the feedback received from the shop floor and modify the knowledge-base accordingly. As different estimates of a fuzzy variable are decided based on expert's opinion, there is a need to optimize these estimates to enhance performance. For this purpose, a series of experiments are conducted and the best of an expert's knowledge and experimental data are combined to develop a methodology to predict the optimal membership grades for fuzzy variables. In setup planning, surface roughness of the datum face is an important criterion for the selection of datum as it can affect the tolerances among the features. The effect of datum surface roughness on two geometric tolerances, *viz.* parallelism and perpendicularity is studied with a series of experiments done in a vertical milling machine and a universal milling machine. The knowledge gained from the experimental study is incorporated into the setup planning expert system in the form of IF-THEN rules. The knowledge is used to decide the datum surface roughness for

achieving a particular tolerance level. The setup planning expert system also considers fixturing aspects and provides recommended range of depth of cut/feed, machining and clamping forces in fuzzy form, approximate optimal locator and clamp layout, and sizes of the locators and clamps. The uncertainties associated with the work material, clamp material and clamping torque are considered by means of fuzzy arithmetic.

The conclusions of the thesis can be summarized as follows:

- By executing the setup planning expert system for different example parts, it is observed that setup plans are obtained investing very limited amount of time. Given the information about different features present in a part, machining operations, machine tools, cutting tools and material properties as input, the developed setup planning system performs the tasks of setup formation, operation sequencing, datum selection for each setup, and generation of information related to fixturing.
- From the experiments on burr formation in drilling, it is observed that input fuzzy parameters (ductility, feed rate, and tool geometry) have varying effect on burr height. At the same cutting condition, the burr height is the maximum (0.40 mm) for aluminium which is a ductile material. For both aluminium and mild steel, there is significant increase in burr height with increase in feed rate. Variation of burr height with feed rate is not significant in case of cast iron.
- Fine tuning of the initial expert's estimates of fuzzy input parameters has enhanced the performance of the burr height prediction methodology. For the three workpiece materials used (aluminium, mild steel and cast iron), there is a better matching of predicted and observed membership grades for burr heights, with fine tuned values of fuzzy input parameters than with initial expert's values. This ensures the validity of the proposed methodology for fine tuning the initial membership grades of fuzzy parameters.
- From the experiments on effect of datum roughness on parallelism and perpendicularity tolerances, it is observed that both parallelism and

perpendicularity tolerances are the least for the highest datum roughness case (6.35  $\mu\text{m}$ ) than low datum roughness cases. There is no significant change in top surface roughness with change in datum roughness.

- There is significant difference in parallelism and perpendicularity tolerances for low and high datum roughness cases as confirmed from significance test. Based on the knowledge gained from the experimental study, the datum roughness can be ascertained for attaining a particular tolerance level.
- It is observed from the experiments, that rough datum is providing better parallelism and perpendicularity tolerances than the smooth datum. It is due to two opposing effects, machine tool error and elastic deflection of the workpiece. It is concluded that with rough datum, the deflection of the workpiece is more.
- For generation of information related to fixturing, the uncertainties associated with the work material, clamp material and clamping torque are considered by means of fuzzy arithmetic. The developed methodology provides input to fixture designer in terms of range of recommended depth of cut/feed, fuzzy machining and clamping forces, approximate optimal locator and clamp layout and sizes of the locators and clamps in addition to normal setup planning information.
- It is observed from the example parts presented in the thesis that optimized locator and clamp layout gives a much lower value of the norm of the locator reactions than the value given by the initial locator and clamp layout [Section 6.4, Chapter 6 and Section 7.1, Chapter 7]. A strategy is developed to find the dimensions of the locators and clamps.

## 8.2 Contributions of the Research Work

- Most of the previous works dealing with uncertainty considered the uncertainty in shop floor and resources, *e.g.* resource and capacity constraints, machine breakdown, and tool failure. The present setup planning system is capable of dealing with uncertainty in the knowledge-

base. The fuzzy set based approach used to manage uncertainty in the knowledge-base, in particular feature precedence relations and datum selection, gives agreeable results.

- The setup planning system is capable of adaptive learning based on shop floor feedback. The setup plan provides a checklist for certain conditions to be monitored during actual machining stage in the shop floor. For example, if desired tolerances are not achieved/ higher size burrs are produced during drilling holes/or wrong face is selected as datum, this information is fed back so that the necessary modifications are made.
- The methodology developed for fine tuning of the initial expert's estimates of fuzzy parameters has enhanced the performance of the burr height prediction method. This ensures the validity of the proposed methodology for fine tuning the initial membership grades of fuzzy parameters.
- In the literature, not much work is available that relates the effect of datum surface roughness to the geometrical tolerances of a component. In this work, an experimental study is conducted to study the effect of datum surface roughness on parallelism and perpendicularity tolerances. Based on the knowledge gained from the experimental study, the datum surface roughness can be ascertained for attaining a particular tolerance level.
- Most of the existing setup planning systems deals with the conceptual fixture design phase by selecting the datum features. The proposed setup planning system performs configuration design and preliminary detailed design of fixtures in addition to selection of datum. The setup plan provides sufficient input to the fixture designer in terms of range of recommended depth of cut/feed, fuzzy machining and clamping forces, approximate optimal locator and clamp layout and sizes of the locators and clamps.

### 8.3 Scope for Future Work

- In the present work, for implementing the adaptive learning strategy, the inspection engineer/quality control engineer manually checks the status of machining in the shop floor. If some deviation from expected outcome is detected, the information is given to the process planner and the planner makes the necessary changes in the rules in the knowledge-base. Future work can be carried out to make the adaptive learning strategy automated by designing a set of adaptive rules to modify the existing set of rules in the knowledge-base.
- Presently, importance is shifted from stand-alone setup planning system to dynamic setup planning system in geographically distributed manufacturing environment. The recent developments in internet technologies can be utilized to integrate the setup planning expert system with internet to enable exchange of information among different manufacturing organizations located at different sites. Java and Web technologies provide means for the transfer of information between various manufacturing systems. Thus, a part can be designed and manufactured in different sites using the facilities available in a multi-enterprise scenario.
- In this work, machining force is considered static for ensuring stability of the workpiece-fixtured system. To check for static equilibrium of the forces and moments for workpiece-fixtured system, magnitude, direction, and location of machining forces are assumed constant. Future work can be carried out considering dynamic effect of the machining forces which can be studied offline. Finite element method (FEM) and soft computing techniques can be used for analysis of dynamic effect of cutting forces and simulation study can be performed. The effect of material removal rate during machining is also important as inertia of the system decreases with removal of material during machining. Therefore, the dynamic

effect of the machining forces, the effect of material removal rate and change in geometry can be considered in future work.

- In this work, a frictionless contact between the workpiece and fixture elements is assumed leading to a prediction of higher value of clamping force and thus safer fixture design. However, friction can be considered in future works.
- A complete software package can be developed by integrating the setup planning expert system with the other modules of a computer-aided process planning system which will automatically generate all the relevant information for machining a part.



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## Appendix

### Appendix A

#### Calculation of coefficient of variation for the experimental results of effect of datum surface roughness on parallelism and perpendicularity

In a machining process, some inherent statistical variation is always present. To account for the statistical variations, statistical analysis may be employed. A measure of the variability of the experimental results is coefficient of variation (CV), which is computed as

$$CV = \frac{s}{\bar{x}} \times 100, \quad (A1)$$

where  $\bar{x}$  is the sample mean and  $s$  is the standard deviation. CV provides a general idea about the performance of a method. CVs of 5% or less generally give a feeling of good method performance, whereas CVs of 10% and higher are not preferred.

Tables A-1–A-6 show the results of replicate experiments for the machining of cast iron and perspex on the vertical milling machine. The mean ( $\bar{x}$ ), standard deviation ( $s$ ), and range for each datum roughness are calculated. Table A-1 shows the maximum difference between Z coordinates of two points along diagonal D<sub>1</sub> (Figure 5.1, Chapter 5) for cast iron workpiece for 5 replicate experiments.

**Table A-1:** Maximum Z coordinate difference between two points along D<sub>1</sub> for cast iron workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
1.74	0.1682	0.1665	0.1599	0.1698	0.1625	5	0.1654	0.0041	0.0099
2.14	0.1903	0.1952	0.1939	0.2014	0.2021	5	0.1966	0.0051	0.0118
3.29	0.2267	0.2198	0.2194	0.2187	0.2199	5	0.2209	0.0033	0.0080
3.90	0.2318	0.2325	0.2311	0.2345	0.2301	5	0.2320	0.0017	0.0044
4.86	0.0909	0.0887	0.0895	0.0873	0.0899	5	0.0893	0.0014	0.0036
5.43	0.0346	0.0339	0.0365	0.0358	0.0369	5	0.0355	0.0013	0.0030
6.35	0.0162	0.0164	0.0170	0.0165	0.0169	5	0.0166	0.0003	0.0008

For each datum surface roughness provided in Table A-1, CV values are calculated using Equation A1.

At datum  $R_a=1.74 \mu\text{m}$

$$\text{The coefficient of variation (in percentage), } CV = \frac{0.0041}{0.1654} \times 100 = 2.47\%$$

At datum  $R_a=2.14 \mu\text{m}$

$$\text{The coefficient of variation (in percentage), } CV = \frac{0.0051}{0.1966} \times 100 = 2.59\%$$

At datum  $R_a=3.29 \mu\text{m}$

$$\text{The coefficient of variation (in percentage), } CV = \frac{0.0033}{0.2209} \times 100 = 1.49\%$$

At datum  $R_a=3.90 \mu\text{m}$

$$\text{The coefficient of variation (in percentage), } CV = \frac{0.0017}{0.2320} \times 100 = 0.73\%$$

At datum  $R_a=4.86 \mu\text{m}$

$$\text{The coefficient of variation (in percentage), } CV = \frac{0.0014}{0.0893} \times 100 = 1.56\%$$

At datum  $R_a=5.43 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0013}{0.0355} \times 100 = 3.66\%$

At datum  $R_a=6.35 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0003}{0.0166} \times 100 = 1.80\%$

The maximum value of coefficient of variation is 3.66% for a datum surface roughness of 5.43  $\mu\text{m}$ .

Table A-2 shows the maximum difference between Z coordinates of two points along diagonal  $D_2$  (Figure 5.1, Chapter 5) for cast iron workpiece for 5 replicate experiments.

**Table A-2:** Maximum Z coordinate difference between two points along  $D_2$  for cast iron workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
1.74	0.0280	0.0288	0.0331	0.0326	0.0264	5	0.0300	0.0032	0.0067
2.14	0.0277	0.0223	0.0302	0.0252	0.0266	5	0.0264	0.0029	0.0079
3.29	0.0268	0.0301	0.0291	0.0264	0.0275	5	0.0280	0.0016	0.0037
3.90	0.0323	0.0259	0.0301	0.0317	0.0312	5	0.0302	0.0026	0.0064
4.86	0.0414	0.0361	0.0339	0.0416	0.0354	5	0.0377	0.0036	0.0077
5.43	0.0306	0.0250	0.0299	0.0301	0.0294	5	0.0290	0.0023	0.0056
6.35	0.0137	0.0144	0.0143	0.0196	0.0147	5	0.0153	0.0024	0.0059

For each datum surface roughness provided in Table A-2, CV values are calculated using Equation A1.

At datum  $R_a=1.74 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0032}{0.0300} \times 100 = 10.67\%$

At datum  $R_a=2.14 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0029}{0.0264} \times 100 = 10.98\%$

At datum  $R_a=3.29 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0016}{0.0280} \times 100 = 5.71\%$

At datum  $R_a=3.90 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0026}{0.0302} \times 100 = 8.60\%$

At datum  $R_a=4.86 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0036}{0.0377} \times 100 = 9.54\%$

At datum  $R_a=5.43 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0023}{0.0290} \times 100 = 7.93\%$

At datum  $R_a=6.35 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0024}{0.0153} \times 100 = 15.68\%$

The maximum value of coefficient of variation is 15.68% for a datum surface roughness of 6.35  $\mu\text{m}$ .

Tables A-3 and A-4 show the results of replicate experiments for the machining of perspex on the vertical milling machine.

**Table A-3** Maximum Z coordinate difference between two points along  $D_1$  for perspex workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
0.85	0.2989	0.2954	0.2963	0.2985	0.2978	5	0.2973	0.0020	0.0035
2.15	0.3099	0.3008	0.3053	0.3067	0.3073	5	0.3060	0.0033	0.0091
6.35	0.0989	0.1023	0.1096	0.1087	0.1078	5	0.1055	0.0046	0.0107

For each datum surface roughness provided in Table A-3, CV values are calculated using Equation A1.

At datum  $R_a=0.85 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0020}{0.2973} \times 100 = 0.67\%$

At datum  $R_a=2.15 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0033}{0.3060} \times 100 = 1.07\%$

At datum  $R_a=6.35 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0046}{0.1055} \times 100 = 4.36\%$

The maximum value of coefficient of variation is 4.36% for a datum surface roughness of 6.35  $\mu\text{m}$ .

**Table A-4:** Maximum Z coordinate difference between two points along  $D_2$  for perspex workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
0.85	0.0389	0.0416	0.0397	0.0392	0.0381	5	0.0395	0.0013	0.0035
2.15	0.0402	0.0409	0.0407	0.0412	0.0406	5	0.0407	0.0037	0.0010
6.35	0.0326	0.0331	0.0340	0.0348	0.0341	5	0.0337	0.0008	0.0022

For each datum surface roughness provided in Table A-4, CV values are calculated using Equation A1.

At datum  $R_a=0.85 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0013}{0.0395} \times 100 = 3.29\%$

At datum  $R_a=2.15 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0037}{0.0407} \times 100 = 9.09\%$

At datum  $R_a=6.35 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0008}{0.0337} \times 100 = 2.37\%$

The maximum value of coefficient of variation is 9.09% for a datum surface roughness of 2.15  $\mu\text{m}$ .

Tables A-5 and A-6 show the perpendicularity tolerances for cast iron and perspex work pieces respectively for 5 replicates each.

**Table A-5:** Perpendicularity tolerance with varying datum roughness for cast iron workpiece

Datum roughness $R_a (\mu\text{m})$	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
1.74	0.0996	0.0968	0.0993	0.0976	0.0989	5	0.0984	0.0012	0.0028
2.14	0.0934	0.0945	0.0936	0.0962	0.0957	5	0.0947	0.0012	0.0028
3.29	0.0881	0.0884	0.0879	0.0873	0.0879	5	0.0879	0.0004	0.0011
3.90	0.0879	0.0874	0.0881	0.0869	0.0877	5	0.0876	0.0005	0.0012
4.86	0.0766	0.0781	0.0779	0.0788	0.0787	5	0.0782	0.0005	0.0022
5.43	0.0543	0.0568	0.0561	0.0557	0.0545	5	0.0555	0.0011	0.0025
6.35	0.0467	0.0473	0.0455	0.0478	0.0469	5	0.0468	0.0008	0.0023

For each datum surface roughness provided in Table A-5, CV values are calculated using Equation A1.

At datum  $R_a=1.74 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0012}{0.0984} \times 100 = 1.22\%$

At datum  $R_a=2.14 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0012}{0.0947} \times 100 = 1.27\%$

At datum  $R_a=3.29 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0004}{0.0879} \times 100 = 0.46\%$

At datum  $R_a=3.90 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0005}{0.0876} \times 100 = 0.57\%$

At datum  $R_a=4.86 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0005}{0.0782} \times 100 = 0.64\%$

At datum  $R_a=5.43 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0011}{0.0555} \times 100 = 1.98\%$

At datum  $R_a=6.35 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0008}{0.0468} \times 100 = 1.71\%$

The maximum value of coefficient of variation is 1.98% for a datum surface roughness of 5.43  $\mu\text{m}$ .

**Table A-6:** Perpendicularity tolerance with varying datum roughness for perspex workpiece

Datum roughness $R_a$ ( $\mu\text{m}$ )	Replicate1 (mm)	Replicate2 (mm)	Replicate3 (mm)	Replicate4 (mm)	Replicate5 (mm)	Sample size $n$	Sample mean $\bar{x}$ (mm)	Standard deviation $s$ (mm)	Range (mm)
0.85	0.0891	0.0889	0.0897	0.0891	0.0895	5	0.0893	0.0003	0.0008
2.15	0.0872	0.0881	0.0870	0.0879	0.0883	5	0.0877	0.0006	0.0013
6.35	0.0433	0.0446	0.0452	0.0439	0.0442	5	0.0442	0.0007	0.0019

For each datum surface roughness provided in Table A-6, CV values are calculated using Equation A1.

At datum  $R_a=0.85 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0003}{0.0893} \times 100 = 0.34\%$

At datum  $R_a=2.15 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0006}{0.0877} \times 100 = 0.68\%$

At datum  $R_a=6.35 \mu\text{m}$

The coefficient of variation (in percentage),  $CV = \frac{0.0007}{0.0442} \times 100 = 1.58\%$

The maximum value of coefficient of variation is 1.58% for a datum surface roughness of 6.35  $\mu\text{m}$ .

It is observed that in all the cases, the maximum CV values are low (3.66%, 4.36%, 9.09%, 1.98%, and 1.58%), except one case where the value of CV is 15.68%. Hence, the variability among the replicate experiments is low thus confirming a good repeatability.

## Appendix B

### A test of hypothesis to account for the statistical variations present in the experiments of effect of datum surface roughness on parallelism and perpendicularity

When test sample size is small ( $< 30$ ), then the test of significance is carried out based on Student's  $t$ -test. The main application of  $t$ -distribution is to test if the sample mean ( $\bar{x}$ ) differs significantly from the hypothetical value of population mean ( $\mu$ ) and to test the significance of the difference between two sample means  $\bar{x}_1$  and  $\bar{x}_2$ . In the present work, replicate experiments were carried out to study the effect of datum surface roughness on parallelism and perpendicularity tolerances for machining of prismatic parts. The results of replicate experiments were used in two-sample  $t$ -test. Two-sample  $t$ -test is a popular statistical tool for comparison purpose. It is carried out to see whether for two samples of sizes  $m$  and  $n$ , the difference between sample means  $\bar{x}_1$  and  $\bar{x}_2$  is significant or not. For this, the sample means  $\bar{x}_1$  and  $\bar{x}_2$  and the standard deviations  $s_1$  and  $s_2$  of the two samples are calculated. Then the  $t$ -statistic is calculated as

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{((m-1)s_1^2 + (n-1)s_2^2)}{m+n-2} \left[ \frac{1}{m} + \frac{1}{n} \right]}} \quad (\text{B1})$$

Tables A-1–A-6 [Appendix A] show the results of replicate experiments for the machining of cast iron and perspex on the vertical milling machine. The sample size ( $n$ ), sample mean ( $\bar{x}$ ), standard deviation ( $s$ ), and range for each datum roughness are calculated. Based on the data provided in Tables A-1–A-6, a comparison is made between the parallelism and perpendicularity tolerances found with low and high datum roughness cases. To find out whether the differences in the tolerances found

with low and high datum roughness are significant or not, Student's  $t$ -test using 95% confidence level is employed. Let  $\bar{x}_H$  and  $\bar{x}_L$  be the mean of maximum parallelism/perpendicularity tolerance for the highest and the lowest datum roughness cases respectively. The corresponding standard deviations are  $s_H$  and  $s_L$ .

Sample size is equal ( $n$ ) for both the cases. The null hypothesis is taken as:

$H_0$ : The difference in parallelism/perpendicularity tolerance for low and high datum roughness is not significant, *i.e.*

$$\bar{x}_H - \bar{x}_L = 0 \quad (B2)$$

The alternative hypothesis considered (for one-sided test) is

$H_1$ : Parallelism/perpendicularity tolerance for high datum roughness is lower than that of low datum roughness, *i.e.*

$$\bar{x}_H < \bar{x}_L \quad (B3)$$

Now,  $\bar{x}_1 = \bar{x}_L$ ,  $\bar{x}_2 = \bar{x}_H$ ,  $s_1 = s_L$ ,  $s_2 = s_H$ , and  $m = n$  in Equation B1. Therefore

Equation B1 reduces to

$$t = \frac{\bar{x}_L - \bar{x}_H}{\sqrt{\frac{(s_L^2 + s_H^2)}{n}}} \quad (B4)$$

### Case-1

From Table A-1, high datum roughness = 6.35  $\mu\text{m}$ , low datum roughness = 1.74  $\mu\text{m}$ ,  $\bar{x}_L = 0.1654$ ,  $\bar{x}_H = 0.0166$ ,  $s_L = 0.0041$ ,  $s_H = 0.0003$ , and  $n = 5$

Using Equation B4,

$$t = \frac{0.1614 - 0.0166}{\sqrt{\frac{(0.0041^2 + 0.0003^2)}{5}}} = 80.94$$

Case-2

From Table A-2, high datum roughness = 6.35  $\mu\text{m}$ , low datum roughness = 1.74  $\mu\text{m}$ ,

$\bar{x}_L = 0.0300$ ,  $\bar{x}_H = 0.0153$ ,  $s_L = 0.0032$ ,  $s_H = 0.0024$ , and  $n = 5$

Using Equation B4,

$$t = \frac{0.0300 - 0.0153}{\sqrt{\frac{(0.0032^2 + 0.0024^2)}{5}}} = 8.22$$

Case-3

From Table A-3, high datum roughness = 6.35  $\mu\text{m}$ , low datum roughness = 0.85  $\mu\text{m}$ ,

$\bar{x}_L = 0.2973$ ,  $\bar{x}_H = 0.1055$ ,  $s_L = 0.0020$ ,  $s_H = 0.0046$ , and  $n = 5$

Using Equation B4,

$$t = \frac{0.2973 - 0.1055}{\sqrt{\frac{(0.0020^2 + 0.0046^2)}{5}}} = 85.50$$

Case-4

From Table A-4, high datum roughness = 6.35  $\mu\text{m}$ , low datum roughness = 0.85  $\mu\text{m}$ ,

$\bar{x}_L = 0.0395$ ,  $\bar{x}_H = 0.0337$ ,  $s_L = 0.0013$ ,  $s_H = 0.0008$ , and  $n = 5$

Using Equation B4,

$$t = \frac{0.0395 - 0.0337}{\sqrt{\frac{(0.0013^2 + 0.0008^2)}{5}}} = 8.78$$

Case-5

From Table A-5, high datum roughness = 6.35  $\mu\text{m}$ , low datum roughness = 1.74  $\mu\text{m}$ ,

$\bar{x}_L = 0.0984$ ,  $\bar{x}_H = 0.0468$ ,  $s_L = 0.0012$ ,  $s_H = 0.0008$ , and  $n = 5$

Using Equation B4,

$$t = \frac{0.0984 - 0.0468}{\sqrt{\frac{(0.0012^2 + 0.0008^2)}{5}}} = 80$$

Case-6

From Table A-6, high datum roughness = 6.35  $\mu\text{m}$ , low datum roughness = 0.85  $\mu\text{m}$ ,  $\bar{x}_L = 0.0893$ ,  $\bar{x}_H = 0.0442$ ,  $s_L = 0.0003$ ,  $s_H = 0.0007$ , and  $n = 5$

Using Equation B4,

$$t = \frac{0.0893 - 0.0442}{\sqrt{\frac{(0.0003^2 + 0.0007^2)}{5}}} = 132.42$$

At the 5% significance level and for 8 degrees of freedom ( $m+n-2=8$ ), the critical value of  $t$  denoted as  $t_{0.05}$  is 1.86 for one-sided test [Logothetis, 1997]. Considering all the cases, it is observed that the value of  $t$  in the  $t$ -test is found to be much higher than the value of  $t_{0.05}$ . As  $|t| > t_{0.05}$ , the null hypothesis is rejected. Conclusion can be drawn at 95% confidence interval that there is significant difference in parallelism/perpendicularity tolerance for low and high datum roughness cases. Parallelism/perpendicularity tolerance for high datum roughness is lower than that for low datum roughness.

## Appendix C

### A contact mechanics based approach for modelling of contact condition between the workpiece and the fixture

Hertz's contact model can be used to represent the contact condition between two elastic bodies in contact [Johnson, 1985]. Considering the workpiece and the fixture as elastic bodies, Hertz's contact mechanics approach is used for modelling workpiece-fixture contact conditions. When two non-conforming (of dissimilar profile) bodies are in contact, they initially touch at a single point or a line. When load is applied, deformation occurs and point/line contact becomes area contact. However, the contact area is small compared to the dimensions of the contacting bodies. The study is restricted to two bodies in contact where the contact area is a circle of radius  $a$ . Hertz's contact model holds good for two bodies of general shape (two spheres or a sphere-plane) in contact. The contact area, contact deformation and compressive load can be found from Hertz's contact model. In this study, all the calculations are based on Johnson (1985). When the workpiece and the fixture element are in contact, the pressure distributed over the circular contact area of radius  $a$  is given by

$$p(r) = p_{\max} \left( 1 - \frac{r^2}{a^2} \right)^{\frac{1}{2}}, \quad (C1)$$

where  $r$  is the radius at any point of the contact circle ( $r < a$ ) and  $p_{\max}$  is the maximum contact pressure. Considering a ring at radius  $r$  with area  $2\pi r dr$ , load on the annulus is  $p(r) 2\pi r dr$ . Now the total compressive load  $P$  on the contact circle is given by

$$P = \int_0^a p(r) 2\pi r dr \quad (C2)$$

Putting the value of  $p(r)$  from Equation (C1) in Equation (C2)

$$P = \int_0^a p_{\max} \sqrt{\frac{a^2 - r^2}{a^2}} 2\pi r dr$$

$$P = \frac{2\pi p_{\max}}{a} \int_0^a \sqrt{a^2 - r^2} r dr$$

Let

$$a^2 - r^2 = t$$

$$-2r dr = dt$$

$$r dr = -\frac{dt}{2}$$

$$\therefore P = \frac{2\pi p_{\max}}{a} \int_{a^2}^0 t^{\frac{1}{2}} \frac{(-dt)}{2}$$

$$P = \frac{\pi p_{\max}}{a} \int_0^{a^2} t^{\frac{1}{2}} dt$$

$$P = \frac{\pi p_{\max}}{a} \frac{2}{3} \left( t^{\frac{3}{2}} \right)_0^{a^2}$$

$$P = \frac{2}{3} \pi p_{\max} a^2 \quad (C3)$$

Spherical locator and clamp contact surfaces are used in this work. If  $R_w$  and  $R_f$  are the radii of curvature of the workpiece and fixture element contact surface,  $R$  is the relative radius of curvature of the two bodies in contact,  $E_w$  and  $E_f$  are the Young's moduli of elasticity of the workpiece and fixture element,  $E$  is the relative Young's modulus of elasticity,  $\nu_w$  and  $\nu_f$  are the Poisson's ratios of the workpiece and fixture element, then

$$\frac{1}{R} = \frac{1}{R_w} + \frac{1}{R_f} \quad (C4)$$

$$\frac{1}{E} = \frac{1-\nu_w^2}{E_w} + \frac{1-\nu_f^2}{E_f} \quad (C5)$$

Radius of the contact area circle is much smaller compared to the relative radius of curvature  $R$  of the two contacting bodies, *i.e.*  $a \ll R$ .

The radius  $a$  of contact area circle is given by

$$a = \frac{\pi p_{\max} R}{2E} = \left( \frac{3PR}{4E} \right)^{\frac{1}{3}} \quad (C6)$$

Total contact area  $A$  is given by

$$A = \pi a^2 = \pi \left( \frac{3PR}{4E} \right)^{\frac{2}{3}} \quad (C7)$$

The normal contact deformation  $\delta_n$  due to normal load  $P$  at the workpiece-fixture interface is given by

$$\delta_n = \frac{a^2}{R} = \left( \frac{9P^2}{16RE^2} \right)^{\frac{1}{3}} \quad (C8)$$

From Equation (C3), maximum pressure  $p_{\max}$  is given by

$$p_{\max} = \frac{3P}{2\pi a^2} = \left( \frac{6PE^2}{\pi^3 R^2} \right)^{\frac{1}{3}} \quad (C9)$$

Now considering the onset of yielding, the load at which yielding begins in case of two bodies in contact is related to the yield point of the softer material through an appropriate yield criterion. According to von Mises' yield criterion,

$$\frac{1}{6} \{ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \} = k^2 = Y^2/3 \quad (C10)$$

According to Tresca's yield criterion,

$$\max \{ |\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1| \} = 2k = Y \quad (C11)$$

where  $\sigma_1, \sigma_2,$  and  $\sigma_3$  are the principal stresses,  $k$  is the shear yield stress, and  $Y$  is the yield stress of the softer material.

For the spherical tipped fixture and planer workpiece,  $\sigma_1 = \sigma_r, \sigma_2 = \sigma_\theta,$  and  $\sigma_3 = \sigma_z$  and  $\sigma_r = \sigma_\theta$ . Using von Mises' yield criterion, from Equation (C10),

$$\begin{aligned} & \{ (\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_r)^2 \} = 2Y^2 \\ \Rightarrow & \{ (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_r)^2 \} = 2Y^2 \quad (\because \sigma_r = \sigma_\theta) \\ \Rightarrow & (\sigma_z - \sigma_r)^2 = Y^2 \\ \Rightarrow & (\sigma_z - \sigma_r) = Y \end{aligned}$$

$$\begin{aligned}\Rightarrow 0.62 p_{\max} &= Y && (\because \max |\sigma_z - \sigma_r| \text{ for } \nu=0.3 \text{ is } 0.62 p_{\max}) \\ \Rightarrow p_{\max} &= 1.6 Y \\ \Rightarrow p_{\max} &= 1.6\sqrt{3} k = 2.8 k && (\text{as } Y = \sqrt{3} k)\end{aligned}$$

Therefore according to von Mises' yield criterion,  $p_{\max} = 2.8k = 1.6Y$ . Similarly, it can be shown that according to Tresca's yield criterion,  $p_{\max} = 3.2k = 1.6Y$ . The load  $P_y$  to initiate yield in the workpiece material is related to the maximum contact pressure  $p_{\max}$  by the following relation

$$P_y = \frac{\pi^3 R^2}{6E^2} (p_{\max})^3 \quad (\text{C12})$$

Replacing  $p_{\max}$  with  $1.6 Y$  in Equation (C12),  $P_y$  is given by

$$P_y = \frac{\pi^3 R^2}{6E^2} (1.6Y)^3 \quad (\text{C13})$$

Therefore, it is evident from Equation (C13) that to carry a high load without yielding, it is desirable to combine high yield strength with a low elastic modulus.

---

## Appendix D

### Development of the expert system software using CLIPS expert system shell for setup planning of prismatic parts

The program developed in CLIPS to show the implementation of the setup planning expert system (described in Chapter 3) is presented here. The program has been tested using the CLIPS expert system shell 6.3 compiler under the Windows environment. It contains the rules comprising the knowledge-base for solving different setup planning problems as well as the templates used for different facts and functions as explained in Chapter 3. The knowledge-base contains rules for generation of machining precedence constraints, setup formation, machining operation and setup sequencing and selection of datum for each setup. Another data file (datafile .clp) is presented containing the input data for Example Part 1 discussed in Section 7.1.1, Chapter 7. At the time of execution of the expert system program, the following steps are to be performed.

- Load the program file from the knowledge-base into the CLIPS environment using the option 'Load CLIPS Construct' from File menu.
- Load input data (datafile .clp) from database into the CLIPS environment using the option 'Load CLIPS Construct' from File menu.
- Execution of the program is performed by first selecting 'Reset' and then 'Run' options from the Execution menu.

The programs developed in CLIPS for solving different setup planning problems for machining of prismatic parts are given hereunder:

**;;;\* DEFTEMPLATE DEFINITIONS \***

**;;;The following feature facts hold the information on each feature such as identification number, name, type, sub-type, reference features, adjacent features, feature dimensions,TAD etc.**

```
(deftemplate MAIN::feature
  (slot number(type INTEGER)(default ?NONE))
  (slot name(type SYMBOL)(allowed-symbols FACE CHAMFER HOLE POCKET STEP
SLOT PRIMARY-DATUM-SETUP-1 PRIMARY-DATUM-SETUP-2 ))
  (slot type(type SYMBOL)(allowed-symbols EXTERNAL INTERNAL))
  (slot subtype(type SYMBOL)(allowed-symbols PRIMARY SECONDARY NESTED
NESTING ABUTTED BASE INTERACTING))
  (slot feature_doc(type NUMBER))
  (slot interacting_feature_doc(type NUMBER))
  (slot face_length(type NUMBER))
  (slot face_breadth(type NUMBER))
  (multislot perp_to(type INTEGER)(default 0))
  (multislot interacting_with(type INTEGER)(default 0))
  (multislot secondary_to(type INTEGER)(default 0))
  (multislot nested_in(type INTEGER)(default 0))
  (multislot abutted_from(type INTEGER)(default 0))
  (multislot adjacent_features(type INTEGER)(default ?NONE))
  (multislot adjacent_features_names(type SYMBOL)(allowed-symbols FACE CHAMFER
HOLE POCKET STEP SLOT ))
  (multislot reference_features(type INTEGER)(default 0))
  (multislot reference_features_names(type SYMBOL)(allowed-symbols FACE HOLE SLOT))
  (multislot TAD(type SYMBOL)(allowed-symbols AD-1 AD-2 AD-3 AD-4 AD-5 AD-6)))
```

**;;;The following operation facts hold the information on each machining operation such as identification number, type,feature to be machined, geometric tolerance, TAD etc.**

```
(deftemplate MAIN::operation
  (slot number(type INTEGER)(default ?NONE))
  (slot type(type SYMBOL)(default ?NONE))
  (slot on_feature(type INTEGER)(default ?NONE))
  (multislot TAD (type SYMBOL)(allowed-symbols AD-1 AD-2 AD-3 AD-4 AD-5 AD-
6)(default ?NONE))
  (slot tool(type SYMBOL)(allowed-symbols end-mill square-end-mill drill chamfer-tool))
  (multislot relation_with_feature(type INTEGER)(default 0))
  (multislot tolerance(type NUMBER)(default 0)))
```

```
(deftemplate MAIN::operation_precedence(multislot values))
```

```
(deftemplate MAIN::TAD_AD-1_feature_cluster(multislot operation_numbers))
(deftemplate MAIN::TAD_AD-2_feature_cluster(multislot operation_numbers))
(deftemplate MAIN::TAD_AD-3_feature_cluster(multislot operation_numbers))
(deftemplate MAIN::TAD_AD-4_feature_cluster(multislot operation_numbers))
(deftemplate MAIN::TAD_AD-5_feature_cluster(multislot operation_numbers))
(deftemplate MAIN::TAD_AD-6_feature_cluster(multislot operation_numbers))
(deftemplate MAIN::setup-1_feature_cluster(multislot operation_numbers))
(deftemplate MAIN::setup-2_feature_cluster(multislot operation_numbers))
```

**;;;The following modified operation facts hold the information on each machining operation such as identification number, type,setup clusters, preceding operations etc.**

```
(deftemplate MAIN::opn
  (slot number (type INTEGER) (default ?NONE))
  (slot type (type SYMBOL) (default ?NONE))
  (slot TAD_cluster(type SYMBOL)(allowed-symbols AD-1 AD-2 AD-3 AD-4 AD-5 AD-6))
  (slot tool(type SYMBOL)(allowed-symbols end-mill square-end-mill drill chamfer-tool))
  (slot setup(type SYMBOL)(allowed-symbols setup-1 setup-2 setup-3))
  (multislot preceding_opn (type INTEGER) (default 0)))
```

### **::: \* DEFFUNCTIONS \***

**:::The following function is used to return the order of precedence between features based on machining of reference features first**

```
(deffunction MAIN::function1 (?f1 ?a)
  (bind $?number(fact-slot-value ?f1 reference_features))
  (while (>=(length$ $?number)1)
    (bind ?number1(first$ $?number))
    (bind $?number(rest$ $?number))
    (assert(feature_precedence ?number1 ?a))))
```

**:::The following functions are used to return the identifier of the feature with which another feature has the tightest tolerance relations**

**:::feature with tightest tolerance case only with one feature**

```
...*****
:::
(deffunction MAIN::feature-with-tightest-tolerance-case-with-one-feature(?f1)
  (bind ?num5(nth$ 1(fact-slot-value ?f1 relation_with_feature)))
  return ?num5)
```

**:::feature with tolerance relations with multiple features having only one TAD**

```
...*****
:::
(deffunction MAIN::feature-with-tightest-tolerance (?f1)
  (bind $?num(fact-slot-value ?f1 tolerance))
  (while(>=(length$ ?num)2)
    (bind ?num1(first$ ?num))
    (bind ?num2(rest$ ?num))
    (bind ?num2(first$ ?num))
    (bind ?num11(nth$ 1(create$ ?num1)))
    (bind ?num22(nth$ 1(create$ ?num2)))
    (if(> ?num11 ?num22)
      then(bind ?num1 ?num2)
      else(bind ?num1 ?num1)))
    (bind ?num3(member$ (create$ ?num1) (fact-slot-value ?f1 tolerance)))
    (bind ?num4(nth$ ?num3 (fact-slot-value ?f1 relation_with_feature)))
    return ?num4)
```

**:::tightest tolerance value of the feature with tolerance relations with multiple features having only one TAD**

```
(deffunction MAIN::tightest-tolerance (?f1)
  (bind ?num(fact-slot-value ?f1 tolerance))
  (while(>=(length$ ?num)2)
    (bind ?num1(first$ ?num)(bind ?num(rest$ ?num))
    (bind ?num2(first$ ?num))
    (bind ?num11(nth$ 1(create$ ?num1)))(bind ?num22(nth$ 1(create$ ?num2)))
    (if(> ?num11 ?num22)then(bind ?num1 ?num2)else(bind ?num1 ?num1)))
    return ?num1)
```

**;;;The following functions are used to update the tolerance relationship vectors by removing those tolerance relationship between features that have been already satisfied**

```
(deffunction MAIN::update-relation-with-feature (?f1)
  (bind ?num (fact-slot-value ?f1 relation_with_feature))
  (bind ?num1 (feature-with-tightest-tolerance ?f1))
  (bind ?num2 (delete-member$ (create$ ?num) ?num1))
  (return ?num2))
(deffunction MAIN::update-tolerance (?f1)
  (bind ?num (fact-slot-value ?f1 tolerance))
  (bind ?num1 (tightest-tolerance ?f1))
  (bind ?num2 (delete-member$ (create$ ?num) ?num1))
  (return ?num2))
```

### **;;; \* RULES FOR GENERATING PRECEDENCE CONSTRAINTS BETWEEN FEATURES**

**;;;The following rules are used for generating precedence constraints between machining operation on features based on expert knowledge and heuristics**

```
(defrule MAIN::precedence_constraint_1_locating "precedence based on machining of reference features first"
  ?f1<-(feature(number ?a)(reference_features $?b))
  (test (> (nth$ 1(create$ $?b) 0))
=> (function1 ?f1 ?a))

(defrule MAIN::precedence_constraint_2 "precedence based on machining of a face prior to that of the adjacent blind hole"
  (feature(number ?a)(name HOLE)(type INTERNAL)(subtype SECONDARY)(adjacent_features ?b)(adjacent_features_names FACE))
=> (assert(feature_precedence ?b ?a)))

(defrule MAIN::precedence_constraint_3 "precedence based on machining of faces prior to that of the adjacent through hole"
  (feature(number ?a)(name HOLE)(type INTERNAL)(subtype SECONDARY)(adjacent_features ?b ?c)(adjacent_features_names FACE FACE))
=> (assert(feature_precedence ?b ?a))
  (assert(feature_precedence ?c ?a)))

(defrule MAIN::precedence_constraint_4 "precedence based on machining of adjacent face prior to that of the adjacent step"
  (feature (number ?a)(name STEP)(type EXTERNAL)(subtype SECONDARY)(secondary_to ?b))
=> (assert(feature_precedence ?b ?a)))

(defrule MAIN::precedence_constraint_5 "precedence based on machining of adjacent face prior to that of the adjacent slot"
  (feature (number ?a)(name SLOT)(type EXTERNAL)(subtype SECONDARY)(secondary_to ?b))
=> (assert(feature_precedence ?b ?a)))

(defrule MAIN::precedence_constraint_6 "precedence based on machining of a face prior to that of the adjacent pocket"
  (feature (number ?a)(name POCKET)(type INTERNAL)(subtype SECONDARY)(secondary_to ?b))
=> (assert(feature_precedence ?b ?a)))
```

---

```
(defrule MAIN::precedence_constraint_7 "precedence based on machining of faces prior to that of the adjacent pocket"
```

```
  (feature (number ?a)(name POCKET)(type INTERNAL)(subtype
SECONDARY)(secondary_to ?b ?c))
=>  (assert(feature_precedence ?b ?a))
    (assert(feature_precedence ?c ?a)))
```

```
(defrule MAIN::precedence_constraint_8 "precedence based on machining of the two faces prior to that of the chamfer between them"
```

```
  (feature(number ?a)(name CHAMFER)(type EXTERNAL)(subtype
SECONDARY)(secondary_to ?b ?c))
=>  (assert(feature_precedence ?b ?a))
    (assert(feature_precedence ?c ?a)))
```

```
(defrule MAIN::precedence_constraint_9 "precedence based on drilling of a hole on the chamfered face prior to that of chamfer"
```

```
  (feature(number ?a)(name CHAMFER)(type EXTERNAL)(subtype
SECONDARY)(secondary_to ?b)(adjacent_features ?b)(adjacent_features_names HOLE))
=>  (assert(feature_precedence ?b ?a)))
```

```
(defrule MAIN::precedence_constraint_10 "precedence based on machining of adjacent external steps prior to that of the slot between them"
```

```
  (feature (number ?a)(name SLOT)(type EXTERNAL)(subtype
SECONDARY)(adjacent_features ?b ?c)(adjacent_features_names STEP STEP))
=>  (assert(feature_precedence ?b ?a))
    (assert(feature_precedence ?c ?a)))
```

```
(defrule MAIN::precedence_constraint_11 "precedence based on machining of nesting features prior to the nested features"
```

```
  (feature (number ?a)(type INTERNAL)(subtype NESTED )(nested_in ?b))
=>  (assert(feature_precedence ?b ?a)))
```

```
(defrule MAIN::precedence_constraint_12 "precedence based on machining of base features prior to the abutted features"
```

```
  (feature (number ?a)(type INTERNAL)(subtype ABUTTED)(abutted_from ?b))
=>  (assert(feature_precedence ?b ?a)))
```

```
(defrule MAIN::precedence_constraint_13 "precedence based on machining of interacting features with lower doc first"
```

```
  (feature (number ?a)(subtype INTERACTING)(feature_doc ?d1)(interacting_with
?b)(interacting_feature_doc ?d2))
  (test(< ?d1 ?d2))
=>  (assert(feature_precedence ?a ?b)))
```

```
(defrule MAIN::precedence_constraint_14 "precedence based on machining of interacting features with lower doc first"
```

```
  (feature (number ?a)(subtype INTERACTING)(feature_doc ?d1)(interacting_with
?b)(interacting_feature_doc ?d2))
  (test(> ?d1 ?d2))
=>  (assert(feature_precedence ?b ?a)))
```

```
(defrule MAIN::precedence_constraint_15 "precedence based on machining of interacting features with equal doc "
```

```
  (feature (number ?a)(subtype INTERACTING)(feature_doc ?d1)(interacting_with
?b)(interacting_feature_doc ?d2))
  (test(= ?d1 ?d2))
```

```
=> (assert(feature_precedence ?a ?b))
    (assert(feature_precedence ?b ?a)))
```

**;;;\*RULES FOR GENERATING PRECEDENCE CONSTRAINTS BETWEEN OPERATIONS\***

```
(defrule MAIN::operation_precedence_constraint
  (operation (number ?n1)(on_feature ?a))
  (operation (number ?n2)(on_feature ?b))
  (feature_precedence ?a ?b)
=> (assert(operation_precedence (values ?n1 ?n2))))
```

**;;; \* RULES FOR TAD GROUP CLUSTERING \***

**;;;The following rules are used to assign features with multiple TADs having no tolerance relations with other features into setups**

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_no_tolerance_relation_with_feature_1
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-1 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(=(length$ (fact-slot-value ?f1 relation_with_feature))0))
=> (modify ?f1(TAD AD-1))
    (modify ?f2(TAD AD-1)))
```

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_no_tolerance_relation_with_feature_2
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-2 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(=(length$ (fact-slot-value ?f1 relation_with_feature))0))
=> (modify ?f1(TAD AD-2))
    (modify ?f2(TAD AD-2)))
```

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_no_tolerance_relation_with_feature_3
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-3 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(=(length$ (fact-slot-value ?f1 relation_with_feature))0))
=> (modify ?f1(TAD AD-3))
    (modify ?f2(TAD AD-3)))
```

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_no_tolerance_relation_with_feature_4
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-4 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(=(length$ (fact-slot-value ?f1 relation_with_feature))0))
=> (modify ?f1(TAD AD-4))
    (modify ?f2(TAD AD-4)))
```

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_no_tolerance_relation_with_feature_5
  (declare (salience 1000))
```

---

```

?f1 <-(operation(TAD $? AD-5 $?)(on_feature ?on_feature))
?f2 <-(feature(number ?on_feature))
(test=(length$ (fact-slot-value ?f1 relation_with_feature))0))
=> (modify ?f1(TAD AD-5))
    (modify ?f2(TAD AD-5))

```

```

(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_no_tolerance_relation_with_feature_6
  (declare (saliency 1000))
  ?f1 <-(operation(TAD $? AD-6 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test=(length$ (fact-slot-value ?f1 relation_with_feature))0))
=> (modify ?f1(TAD AD-6))
    (modify ?f2(TAD AD-6))

```

**;;;The following rules are used to assign a specific TAD to operations on features with multiple  
 ;;;TADs having tolerance relations with only one feature having single TAD**

```

(defrule MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_one_feature_1
  (declare (saliency 1000))
  ?f1 <-(operation(TAD $? AD-1 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test=(length$ (fact-slot-value ?f1 tolerance))1))
  (operation(TAD AD-1)(on_feature =(feature-with-tightest-tolerance-case-with-one-feature
?f1))))
=> (modify ?f1(TAD AD-1)(relation_with_feature 0)(tolerance 0))
    (modify ?f2(TAD AD-1))

```

```

(defrule MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_one_feature_2
  (declare (saliency 1000))
  ?f1 <-(operation(TAD $? AD-2 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test=(length$ (fact-slot-value ?f1 tolerance))1))
  (operation(TAD AD-2)(on_feature =(feature-with-tightest-tolerance-case-with-one-feature
?f1))))
=> (modify ?f1(TAD AD-2)(relation_with_feature 0)(tolerance 0))
    (modify ?f2(TAD AD-2))

```

```

(defrule MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_one_feature_3
  (declare (saliency 1000))
  ?f1 <-(operation(TAD $? AD-3 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test=(length$ (fact-slot-value ?f1 tolerance))1))
  (operation(TAD AD-3)(on_feature =(feature-with-tightest-tolerance-case-with-one-feature
?f1))))
=> (modify ?f1(TAD AD-3)(relation_with_feature 0)(tolerance 0))
    (modify ?f2(TAD AD-3))

```

```

(defrule MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_one_feature_4
  (declare (saliency 1000))
  ?f1 <-(operation(TAD $? AD-4 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test=(length$ (fact-slot-value ?f1 tolerance))1))
  (operation(TAD AD-4)(on_feature =(feature-with-tightest-tolerance-case-with-one-feature
?f1))))
=> (modify ?f1(TAD AD-4)(relation_with_feature 0)(tolerance 0))
    (modify ?f2(TAD AD-4))

```

```
(defrule MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_one_feature_5
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-5 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(=(length$ (fact-slot-value ?f1 tolerance))1))
  (operation(TAD AD-5)(on_feature =(feature-with-tightest-tolerance-case-with-one-feature
?f1)))
=> (modify ?f1(TAD AD-5)(relation_with_feature 0)(tolerance 0))
    (modify ?f2(TAD AD-5)))
```

```
(defrule MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_one_feature_6
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-6 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(=(length$ (fact-slot-value ?f1 tolerance))1))
  (operation(TAD AD-6)(on_feature =(feature-with-tightest-tolerance-case-with-one-feature
?f1)))
=> (modify ?f1(TAD AD-6)(relation_with_feature 0)(tolerance 0))
    (modify ?f2(TAD AD-6)))
```

**;;;The following rules are used to assign a specific TAD to operations on features with multiple TADs having tolerance relations with more than one feature each having single TAD**

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_multiple_features_with_singl
e_TAD_1
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-1 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(>=(length$ (fact-slot-value ?f1 tolerance))2))
  (operation(TAD AD-1)(on_feature =(feature-with-tightest-tolerance ?f1)))
=> (modify ?f1(TAD AD-1)(relation_with_feature =(update-relation-with-feature ?f1))(tolerance
=(update-tolerance ?f1)))
    (modify ?f2(TAD AD-1)))
```

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_multiple_features_with_singl
e_TAD_2
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-2 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(>=(length$ (fact-slot-value ?f1 tolerance))2))
  (operation(TAD AD-2)(on_feature =(feature-with-tightest-tolerance ?f1)))
=> (modify ?f1(TAD AD-2)(relation_with_feature =(update-relation-with-feature ?f1))(tolerance
=(update-tolerance ?f1)))
    (modify ?f2(TAD AD-2)))
```

```
(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_multiple_features_with_singl
e_TAD_3
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-3 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(>=(length$ (fact-slot-value ?f1 tolerance))2))
  (operation(TAD AD-3)(on_feature =(feature-with-tightest-tolerance ?f1)))
```

```

=> (modify ?f1(TAD AD-3)(relation_with_feature =(update-relation-with-feature ?f1))(tolerance
=(update-tolerance ?f1)))
    (modify ?f2(TAD AD-3))

```

```

(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_multiple_features_with_singl
e_TAD_4
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-4 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(>=(length$ (fact-slot-value ?f1 tolerance))2))
  (operation(TAD AD-4)(on_feature =(feature-with-tightest-tolerance ?f1)))
=> (modify ?f1(TAD AD-4)(relation_with_feature =(update-relation-with-feature ?f1))(tolerance
=(update-tolerance ?f1)))
    (modify ?f2(TAD AD-4))

```

```

(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_multiple_features_with_singl
e_TAD_5
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-5 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(>=(length$ (fact-slot-value ?f1 tolerance))2))
  (operation(TAD AD-5)(on_feature =(feature-with-tightest-tolerance ?f1)))
=> (modify ?f1(TAD AD-5)(relation_with_feature =(update-relation-with-feature ?f1))(tolerance
=(update-tolerance ?f1)))
    (modify ?f2(TAD AD-5))

```

```

(defrule
MAIN::operation_on_feature_with_multiple_TAD_and_relation_with_multiple_features_with_singl
e_TAD_6
  (declare (salience 1000))
  ?f1 <-(operation(TAD $? AD-6 $?)(on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature))
  (test(>=(length$ (fact-slot-value ?f1 tolerance))2))
  (operation(TAD AD-6)(on_feature =(feature-with-tightest-tolerance ?f1)))
=> (modify ?f1(TAD AD-6)(relation_with_feature =(update-relation-with-feature ?f1))(tolerance
=(update-tolerance ?f1)))
    (modify ?f2(TAD AD-6))

```

```

(defrule MAIN::operation_on_chamfer_with_multiple_TAD
  (declare (salience 1000))
  ?f1 <-(operation(TAD ?TAD1 ?TAD2)(type chamfer)( on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature)(name CHAMFER))

=> (modify ?f1(TAD ?TAD2))
    (modify ?f2(TAD ?TAD2))

```

```

(defrule MAIN::operation_on_step_with_multiple_TAD_1
  (declare (salience 1000))
  ?f1 <-(operation(TAD ?TAD1 ?TAD2 ?TAD3)(type mill)( on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature)(name STEP))

=> (modify ?f1(TAD ?TAD3))
    (modify ?f2(TAD ?TAD3))

```

```
(defrule MAIN::operation_on_step_with_multiple_TAD_2
  (declare (salience 1000))
  ?f1 <-(operation(TAD ?TAD1 ?TAD2 ?TAD3 ?TAD4)(type mill)( on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature)(name STEP))
```

```
=> (modify ?f1(TAD ?TAD3))
    (modify ?f2(TAD ?TAD3))
```

```
(defrule MAIN::operation_on_slot_with_multiple_TAD
  (declare (salience 1000))
  ?f1 <-(operation(TAD ?TAD1 ?TAD2 ?TAD3)(type mill)( on_feature ?on_feature))
  ?f2 <-(feature(number ?on_feature)(name SLOT))
```

```
=> (modify ?f1(TAD ?TAD3))
    (modify ?f2(TAD ?TAD3))
```

### **::: \* RULES FOR REPORTING TAD CLUSTERS**

```
(defglobal ?*TAD_AD-1_feature_cluster* = 0
  ?*features_of_TAD_AD-1* = 0
  ?*TAD_AD-2_feature_cluster* = 0
  ?*features_of_TAD_AD-2* = 0
  ?*TAD_AD-3_feature_cluster* = 0
  ?*features_of_TAD_AD-3* = 0
  ?*TAD_AD-4_feature_cluster* = 0
  ?*features_of_TAD_AD-4* = 0
  ?*TAD_AD-5_feature_cluster* = 0
  ?*features_of_TAD_AD-5* = 0
  ?*TAD_AD-6_feature_cluster* = 0
  ?*features_of_TAD_AD-6* = 0)
```

```
(defrule MAIN::features_of_TAD_AD-1
  (declare (salience 500))
  ?f1 <- (operation(TAD $? AD-1 $?))
=> (bind ?*features_of_TAD_AD-1*(fact-slot-value ?f1 number ))
    (bind ?*TAD_AD-1_feature_cluster* (delete-member$(create$ ?*TAD_AD-1_feature_cluster*
  ?*features_of_TAD_AD-1*0)))
```

```
(defrule MAIN::features_of_TAD_AD-2
  (declare (salience 500))
  ?f2 <- (operation(TAD $? AD-2 $?))
=> (bind ?*features_of_TAD_AD-2*(fact-slot-value ?f2 number ))
    (bind ?*TAD_AD-2_feature_cluster* (delete-member$(create$ ?*TAD_AD-2_feature_cluster*
  ?*features_of_TAD_AD-2*0)))
```

```
(defrule MAIN::features_of_TAD_AD-3
  (declare (salience 500))
  ?f3 <- (operation(TAD $? AD-3 $?))
=> (bind ?*features_of_TAD_AD-3*(fact-slot-value ?f3 number ))
    (bind ?*TAD_AD-3_feature_cluster* (delete-member$(create$ ?*TAD_AD-3_feature_cluster*
  ?*features_of_TAD_AD-3*0)))
```

```
(defrule MAIN::features_of_TAD_AD-4
  (declare (salience 500))
  ?f4 <- (operation(TAD $? AD-4 $?))
```

---

```

=> (bind ?*features_of_TAD_AD-4*(fact-slot-value ?f4 number ))
    (bind ?*TAD_AD-4_feature_cluster* (delete-member$(create$ ?*TAD_AD-4_feature_cluster*
?*features_of_TAD_AD-4*)0)))

(defrule MAIN::features_of_TAD_AD-5
(declare (salience 500))
  ?f5 <- (operation(TAD $? AD-5 $?))
=> (bind ?*features_of_TAD_AD-5*(fact-slot-value ?f5 number ))
    (bind ?*TAD_AD-5_feature_cluster* (delete-member$(create$ ?*TAD_AD-5_feature_cluster*
?*features_of_TAD_AD-5*)0)))
(defrule MAIN::features_of_TAD_AD-6
(declare (salience 500))
  ?f6 <- (operation(TAD $? AD-6 $?))
=> (bind ?*features_of_TAD_AD-6*(fact-slot-value ?f6 number ))
    (bind ?*TAD_AD-6_feature_cluster* (delete-member$(create$ ?*TAD_AD-6_feature_cluster*
?*features_of_TAD_AD-6*)0)))

(defrule report-TAD-clusters
=> (printout setup_AD-1 ?*TAD_AD-1_feature_cluster*)
    (close setup_AD-1)
    (printout t "The feature clusters of operations from AD-1 are" ?*TAD_AD-1_feature_cluster*
    crlf)
    (assert (TAD_AD-1_feature_cluster (operation_numbers ?*TAD_AD-1_feature_cluster*)))

    (printout setup_AD-2 ?*TAD_AD-2_feature_cluster*)
    (close setup_AD-2)
    (printout t "The feature clusters of operations from AD-2 are" ?*TAD_AD-2_feature_cluster*
    crlf)
    (assert (TAD_AD-2_feature_cluster (operation_numbers ?*TAD_AD-2_feature_cluster*)))

    (printout setup_AD-3 ?*TAD_AD-3_feature_cluster*)
    (close setup_AD-3)
    (printout t "The feature clusters of operations from AD-3 are" ?*TAD_AD-3_feature_cluster*
    crlf)
    (assert (TAD_AD-3_feature_cluster (operation_numbers ?*TAD_AD-3_feature_cluster*)))

    (printout setup_AD-4 ?*TAD_AD-4_feature_cluster*)
    (close setup_AD-4)
    (printout t "The feature clusters of operations from AD-4 are" ?*TAD_AD-4_feature_cluster*
    crlf)
    (assert (TAD_AD-4_feature_cluster (operation_numbers ?*TAD_AD-4_feature_cluster*)))

    (printout setup_AD-5 ?*TAD_AD-5_feature_cluster*)
    (close setup_AD-5)
    (printout t "The feature clusters of operations from AD-5 are" ?*TAD_AD-5_feature_cluster*
    crlf)
    (assert (TAD_AD-5_feature_cluster (operation_numbers ?*TAD_AD-5_feature_cluster*)))

    (printout setup_AD-6 ?*TAD_AD-6_feature_cluster*)
    (close setup_AD-6)
    (printout t "The feature clusters of operations from AD-6 are" ?*TAD_AD-6_feature_cluster*
    crlf)
    (assert (TAD_AD-6_feature_cluster (operation_numbers ?*TAD_AD-6_feature_cluster*)))

```

**::: \* RULES FOR SETUP GENERATION \***

```
(defglobal ?*setup-1* = 0 ?*setup-2* = 0 ?*setup-3* = 0
?*setup-1_feature_cluster* = 0 ?*setup-2_feature_cluster* = 0)

(defrule MAIN::formation_of_setup-1_R1
  ?f1 <-(TAD_AD-1_feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-1*(fact-slot-value ?f1 operation_numbers))
    (bind ?*setup-1_feature_cluster* (delete-member$(create$ ?*setup-1_feature_cluster*
?*setup-1*0)))

(defrule MAIN::formation_of_setup-1_R2
  ?f1 <-(TAD_AD-2_feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-1*(fact-slot-value ?f1 operation_numbers))
    (bind ?*setup-1_feature_cluster* (delete-member$(create$ ?*setup-1_feature_cluster*
?*setup-1*0)))

(defrule MAIN::formation_of_setup-1_R3
  ?f1 <-(TAD_AD-4_feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-1*(fact-slot-value ?f1 operation_numbers))
    (bind ?*setup-1_feature_cluster* (delete-member$(create$ ?*setup-1_feature_cluster*
?*setup-1*0)))

(defrule MAIN::formation_of_setup-1_R4
  ?f1 <-(TAD_AD-5_feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-1*(fact-slot-value ?f1 operation_numbers))
    (bind ?*setup-1_feature_cluster* (delete-member$(create$ ?*setup-1_feature_cluster*
?*setup-1*0)))

(defrule MAIN::formation_of_setup-1_R5
  ?f1 <-(TAD_AD-6_feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-1*(fact-slot-value ?f1 operation_numbers))
    (bind ?*setup-1_feature_cluster* (delete-member$(create$ ?*setup-1_feature_cluster*
?*setup-1*0)))

(defrule MAIN::formation_of_setup-2_R6
  ?f1 <-(TAD_AD-3_feature_cluster (operation_numbers $?operation_numbers))
=> (bind ?*setup-2*(fact-slot-value ?f1 operation_numbers))
    (bind ?*setup-2_feature_cluster* (delete-member$(create$ ?*setup-2_feature_cluster*
?*setup-2*0)))

(defrule report-setup-1
=> (printout setup-1 ?*setup-1_feature_cluster*)
    (close setup-1)
    (printout t "The feature clusters of setup-1 are" ?*setup-1_feature_cluster* crlf)
    (assert (setup-1_feature_cluster (operation_numbers ?*setup-1_feature_cluster*))))

(defrule report-setup-2
=> (printout setup-2 ?*setup-2_feature_cluster*)
    (close setup-2)
    (printout t "The feature clusters of setup-2 are" ?*setup-2* crlf)
    (assert (setup-2_feature_cluster (operation_numbers ?*setup-2_feature_cluster*))))
```

**::: \* RULES FOR FINDING PRECEDING OPERATIONS FOR EACH OPERATION\***

```

(defrule MAIN::pr-opn-1
  (operation(number ?n1))
  (operation(number ?n2)(type ?type)(TAD $? AD-1 $?)(tool ?tool))
  (operation_precedence (values ?n1 ?n2))
=>
  (assert (opn (number ?n2)(type ?type)(TAD_cluster AD-1)(tool ?tool)(setup setup-1)(preceding_opn ?n1)))
(defrule MAIN::pr-opn-2
  (operation(number ?n1))
  (operation(number ?n2)(type ?type)(TAD $? AD-2 $?)(tool ?tool))
  (operation_precedence (values ?n1 ?n2))
=>
  (assert (opn (number ?n2)(type ?type)(TAD_cluster AD-2)(tool ?tool)(setup setup-1)(preceding_opn ?n1)))

(defrule MAIN::pr-opn-3
  (operation(number ?n1))
  (operation(number ?n2)(type ?type)(TAD $? AD-3 $?)(tool ?tool))
  (operation_precedence (values ?n1 ?n2))
=>
  (assert (opn (number ?n2)(type ?type)(TAD_cluster AD-3)(tool ?tool)(setup setup-2)(preceding_opn ?n1)))

(defrule MAIN::pr-opn-4
  (operation(number ?n1))
  (operation(number ?n2)(type ?type)(TAD $? AD-4 $?)(tool ?tool))
  (operation_precedence (values ?n1 ?n2))
=>
  (assert (opn (number ?n2)(type ?type)(TAD_cluster AD-4)(tool ?tool)(setup setup-1)(preceding_opn ?n1)))

(defrule MAIN::pr-opn-5
  (operation(number ?n1))
  (operation(number ?n2)(type ?type)(TAD $? AD-5 $?)(tool ?tool))
  (operation_precedence (values ?n1 ?n2))
=>
  (assert (opn (number ?n2)(type ?type)(TAD_cluster AD-5)(tool ?tool)(setup setup-1)(preceding_opn ?n1)))

(defrule MAIN::pr-opn-6
  (operation(number ?n1))
  (operation(number ?n2)(type ?type)(TAD $? AD-6 $?)(tool ?tool))
  (operation_precedence (values ?n1 ?n2))
=>
  (assert (opn (number ?n2)(type ?type)(TAD_cluster AD-6)(tool ?tool)(setup setup-1)(preceding_opn ?n1)))

(defrule MAIN::pr-opn-7
  ?f1<-(opn(number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup ?setup)(preceding_opn ?n2))
  ?f2<-(opn(number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup ?setup)(preceding_opn ?n3))
  (test(and(<> ?n2 ?n3)(<> ?n2 0)(<> ?n3 0)))
=>
  ;(retract ?f1 ?f2)
  (assert (opn (number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup ?setup)(preceding_opn ?n2 ?n3)))

(defrule MAIN::pr-opn-8
  ?f1<-(opn(number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup ?setup)(preceding_opn ?n2 ?n3))

```

```
?f3<-(opn(number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup
?setup)(preceding_opn ?n4))
(test(and(<> ?n2 ?n3)(<> ?n2 ?n4)(<> ?n3 ?n4)(<> ?n2 0)(<> ?n3 0)(<> ?n4 0)))
=> ;(retract ?f3)
(assert (opn (number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup
?setup)(preceding_opn ?n2 ?n3 ?n4))))

(defrule MAIN::pr-opn-9
  ?f1<-(opn(number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup
?setup)(preceding_opn ?n2 ?n3 ?n4))
  ?f3<-(opn(number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup
?setup)(preceding_opn ?n5))
  (test(and(<> ?n2 ?n3)(<> ?n2 ?n4)(<> ?n3 ?n4)(<> ?n2 ?n5)(<> ?n3 ?n5)(<> ?n4 ?n5)(<> ?n2
0)(<> ?n3 0)(<> ?n4 0)(<> ?n5 0)))
=> (retract ?f3)
(assert (opn (number ?n1)(type ?type)(TAD_cluster ?TAD)(tool ?tool)(setup
?setup)(preceding_opn ?n2 ?n3 ?n4 ?n5))))

(defrule MAIN::pr-opn-10
  (operation (number ?n) (type ?type)(TAD $? AD-1 $?)(tool ?tool))
  (not (opn (number ?n)))
  (or (operation_precedence (values ?n ?))
      (not (operation_precedence (values ? ?n))))
=>(assert (opn (number ?n) (type ?type) (TAD_cluster AD-1)(tool ?tool)(setup setup-
1)(preceding_opn 0))))

(defrule MAIN::pr-opn-11
  (operation (number ?n) (type ?type)(TAD $? AD-2 $?)(tool ?tool))
  (not (opn (number ?n)))
  (or (operation_precedence (values ?n ?))
      (not (operation_precedence (values ? ?n))))
=> (assert (opn (number ?n) (type ?type) (TAD_cluster AD-2)(tool ?tool)(setup setup-
1)(preceding_opn 0))))

(defrule MAIN::pr-opn-12
  (operation (number ?n) (type ?type)(TAD $? AD-3 $?)(tool ?tool))
  (not (opn (number ?n)))
  (or (operation_precedence (values ?n ?))
      (not (operation_precedence (values ? ?n))))
=> (assert (opn (number ?n) (type ?type) (TAD_cluster AD-3)(tool ?tool)(setup setup-
2)(preceding_opn 0))))

(defrule MAIN::pr-opn-13
  (operation (number ?n) (type ?type)(TAD $? AD-4 $?)(tool ?tool))
  (not (opn (number ?n)))
  (or (operation_precedence (values ?n ?))
      (not (operation_precedence (values ? ?n))))
=> (assert (opn (number ?n) (type ?type) (TAD_cluster AD-4)(tool ?tool)(setup setup-
1)(preceding_opn 0))))

(defrule MAIN::pr-opn-14
  (operation (number ?n) (type ?type)(TAD $? AD-5 $?)(tool ?tool))
  (not (opn (number ?n)))
```

---

```

      (or (operation_precedence (values ?n ?))
          (not (operation_precedence (values ? ?n))))
=> (assert (opn (number ?n) (type ?type) (TAD_cluster AD-5)(tool ?tool)(setup setup-1)(preceding_opn 0)))
(defrule MAIN::pr-opn-15
  (operation (number ?n) (type ?type)(TAD $? AD-6 $?)(tool ?tool))
  (not (opn (number ?n)))
  (or (operation_precedence (values ?n ?))
      (not (operation_precedence (values ? ?n))))
=> (assert (opn (number ?n) (type ?type) (TAD_cluster AD-6)(tool ?tool)(setup setup-1)(preceding_opn 0)))

```

**::: \* RULES FOR GENERATING THE SEQUENCE OF OPERATIONS \***

**::: The following rules are used to determine the sequence of operations for setup-1**

```
(defglobal ?*sequence-setup-1-feature-cluster* = 0)
```

```

(defrule MAIN::sequence-setup-1-feature-cluster-1
  (declare (salience 90))
  ?f1<- (opn (number ?n)(type mill)(tool end-mill)(setup setup-1)(preceding_opn 0))
=> (bind ?opn-setup-1-cluster (fact-slot-value ?f1 number))
   (if (eq ?*sequence-setup-1-feature-cluster* 0)
       then
       (bind ?*sequence-setup-1-feature-cluster*(delete-member$ (create$ ?*sequence-setup-1-
feature-cluster* ?opn-setup-1-cluster) 0))

```

```

  (defrule MAIN::sequence-setup-1-feature-cluster-2
    (declare (salience 89))
    ?f1<- (opn (number ?n1)(type mill)(tool end-mill)(setup setup-1)(preceding_opn ?n2))
    (test (not (= ?n2 0)))
    (opn (number ?n2)(setup setup-1))
=> (bind ?opn-setup-1-cluster (fact-slot-value ?f1 number))
   (if (subsetp (create$ ?n2)(create$ ?*sequence-setup-1-feature-cluster*))
       then
       (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

```

```

  (defrule MAIN::sequence-setup-1-feature-cluster-22
    (declare (salience 88))
    ?f1<- (opn (number ?n1)(type mill)(tool square-end-mill)(setup setup-1)(preceding_opn
?n2))
    (test (not (= ?n2 0)))
    (opn (number ?n2)(setup setup-1))
=> (bind ?opn-setup-1-cluster (fact-slot-value ?f1 number))
   (if (subsetp (create$ ?n2)(create$ ?*sequence-setup-1-feature-cluster*))
       then
       (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

```

```

  (defrule MAIN::sequence-setup-1-feature-cluster-222
    (declare (salience 87))
    ?f1<- (opn (number ?n1)(type drill)(tool drill)(setup setup-1)(preceding_opn ?n2))
    (test (not (= ?n2 0)))
    (opn (number ?n2)(setup setup-1))
=> (bind ?opn-setup-1-cluster (fact-slot-value ?f1 number))
   (if (subsetp (create$ ?n2)(create$ ?*sequence-setup-1-feature-cluster*))
       then

```

```
(bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

(defrule MAIN::sequence-setup-1-feature-cluster-2222
  (declare (salience 86))
  ?f1<- (opn (number ?n1)(type chamfer)(tool chamfer-tool)(setup setup-1)(preceding_opn
?n2))
  (test (not (= ?n2 0)))
  (opn (number ?n2)(setup setup-1))
  => (bind ?opn-setup-1-cluster (fact-slot-value ?f1 number))
  (if (subsetp (create$ ?n2)(create$ ?*sequence-setup-1-feature-cluster*))
  then
  (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

(defrule MAIN::sequence-setup-1-feature-cluster-3
  (declare (salience 86))
  ?f1<- (opn (number ?n1)(setup setup-1)(preceding_opn ?n2 ?n3))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 0)) (not (= ?n3 0))))
  (opn (number ?n2)(setup setup-1))
  (opn (number ?n3)(setup setup-1))
  => (bind ?opn-setup-1-cluster (fact-slot-value ?f1 number))
  (if (subsetp (create$ ?n2 ?n3)(create$ ?*sequence-setup-1-feature-cluster*))
  then
  (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster ))

(defrule MAIN::sequence-setup-1-feature-cluster-4
  (declare (salience 85))
  ?f1<- (opn (number ?n1)(setup setup-1)(preceding_opn ?n2 ?n3))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 0)) (not (= ?n3 0))))
  (not (opn (number ?n2)(setup setup-1)))
  (opn (number ?n3)(setup setup-1))
  => (bind ?opn-setup-1-cluster (fact-slot-value ?f1 number))
  (if (subsetp (create$ ?n3)(create$ ?*sequence-setup-1-feature-cluster*))
  then
  (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

(defrule MAIN::sequence-setup-1-feature-cluster-5
  (declare (salience 84))
  ?f1<- (opn (number ?n1)(setup setup-1)(preceding_opn ?n2 ?n3))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 0)) (not (= ?n3 0))))
  (not (opn (number ?n2)(setup setup-1)))
  (not (opn (number ?n3)(setup setup-1)))
  => (bind ?opn-setup-1-cluster(fact-slot-value ?f1 number))
  (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

(defrule MAIN::sequence-setup-1-feature-cluster-6
  (declare (salience 83))
  ?f1<- (opn (number ?n1)(setup setup-1)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (opn (number ?n2)(setup setup-1))
```

```

      (opn (number ?n3)(setup setup-1))
      (opn (number ?n4)(setup setup-1))
=>   (bind ?opn-setup-1-cluster(fact-slot-value ?f1 number))
      (if (subsetp (create$ ?n2 ?n3 ?n4)(create$ ?*sequence-setup-1-feature-cluster*))
          Then (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-
cluster* ?opn-setup-1-cluster))

(defrule MAIN::sequence-setup-1-feature-cluster-7
  (declare (salience 82))
  ?f1<- (opn (number ?n1)(setup setup-1)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (opn (number ?n2)(setup setup-1))
  (opn (number ?n3)(setup setup-1))
  (not (opn (number ?n4)(setup setup-1)))
=>   (bind ?opn-setup-1-cluster(fact-slot-value ?f1 number))
      (if (subsetp (create$ ?n2 ?n3)(create$ ?*sequence-setup-1-feature-cluster*))
          then
          (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

(defrule MAIN::sequence-setup-1-feature-cluster-8
  (declare (salience 81))
  ?f1<- (opn (number ?n1)(setup setup-1)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (opn (number ?n2)(setup setup-1))
  (not (opn (number ?n3)(setup setup-1)))
  (not (opn (number ?n4)(setup setup-1)))
=>   (bind ?opn-setup-1-cluster(fact-slot-value ?f1 number))
      (if (subsetp (create$ ?n2)(create$ ?*sequence-setup-1-feature-cluster*))
          then
          (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

(defrule MAIN::sequence-setup-1-feature-cluster-9
  (declare (salience 80))
  ?f1<- (opn (number ?n1)(setup setup-1)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (not (opn (number ?n2)(setup setup-1)))
  (not (opn (number ?n3)(setup setup-1)))
  (not (opn (number ?n4)(setup setup-1)))
=>   (bind ?opn-setup-1-cluster(fact-slot-value ?f1 number))
      (bind ?*sequence-setup-1-feature-cluster*(create$ ?*sequence-setup-1-feature-cluster*
?opn-setup-1-cluster))

(defrule report-sequence-setup-1
=>   (printout sequence_setup-1 ?*sequence-setup-1-feature-cluster*)
      (close sequence_setup-1)
      (printout t "The sequence of operations in setup-1 is" ?*sequence-setup-1-feature-cluster*
crLf)
      (assert (The sequence of operations for setup-1 is operation_numbers ?*sequence-setup-1-
feature-cluster*)))

```

;;;The following rules are used to determine the sequence of operations for setup-2

```
(defglobal ?*sequence-setup-2-feature-cluster* = 0)
(defrule MAIN::sequence-setup-2-feature-cluster-1
  (declare (salience 90))
  ?f1<- (opn (number ?n)(type mill)(tool end-mill)(setup setup-2)(preceding_opn 0))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
      (if (eq ?*sequence-setup-2-feature-cluster* 0)
          then
          (bind ?*sequence-setup-2-feature-cluster*(delete-member$ (create$ ?*sequence-setup-2-
feature-cluster* ?opn-setup-2-cluster) 0))
      (defrule MAIN::sequence-setup-2-feature-cluster-2
        (declare (salience 88))
        ?f1<- (opn (number ?n1)(type mill)(tool square-end-mill)(setup setup-2)(preceding_opn
?n2))
        (test (not (= ?n2 0)))
        (opn (number ?n2)(setup setup-2))
        => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
            (if (subsetp (create$ ?n2)(create$ ?*sequence-setup-2-feature-cluster*))
                then
                (bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

(defrule MAIN::sequence-setup-2-feature-cluster-3
  (declare (salience 87))
  ?f1<- (opn (number ?n1)(setup setup-2)(preceding_opn ?n2 ?n3))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 0)) (not (= ?n3 0))))
  (opn (number ?n2)(setup setup-2))
  (opn (number ?n3)(setup setup-2))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
      (if (subsetp (create$ ?n2 ?n3)(create$ ?*sequence-setup-2-feature-cluster*))
          then
          (bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

(defrule MAIN::sequence-setup-2-feature-cluster-4
  (declare (salience 87))
  ?f1<- (opn (number ?n1)(setup setup-2)(preceding_opn ?n2 ?n3))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 0)) (not (= ?n3 0))))
  (not (opn (number ?n2)(setup setup-2)))
  (opn (number ?n3)(setup setup-2))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
      (if (subsetp (create$ ?n3)(create$ ?*sequence-setup-2-feature-cluster*))
          then
          (bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

(defrule MAIN::sequence-setup-2-feature-cluster-5
  (declare (salience 86))
  ?f1<- (opn (number ?n1)(setup setup-2)(preceding_opn ?n2 ?n3))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 0)) (not (= ?n3 0))))
  (not (opn (number ?n2)(setup setup-2)))
  (not (opn (number ?n3)(setup setup-2)))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
```

```

(bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

(defrule MAIN::sequence-setup-2-feature-cluster-6
  (declare (salience 85))
  ?f1<- (opn (number ?n1)(setup setup-2)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (opn (number ?n2)(setup setup-2))
  (opn (number ?n3)(setup setup-2))
  (opn (number ?n4)(setup setup-2))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
  (if (subsetp (create$ ?n2 ?n3 ?n4)(create$ ?*sequence-setup-2-feature-cluster*))
  then
  (bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

(defrule MAIN::sequence-setup-2-feature-cluster-7
  (declare (salience 84))
  ?f1<- (opn (number ?n1)(setup setup-2)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (opn (number ?n2)(setup setup-2))
  (opn (number ?n3)(setup setup-2))
  (not (opn (number ?n4)(setup setup-2)))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
  (if (subsetp (create$ ?n2 ?n3)(create$ ?*sequence-setup-2-feature-cluster*))
  then
  (bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

(defrule MAIN::sequence-setup-2-feature-cluster-8
  (declare (salience 83))
  ?f1<- (opn (number ?n1)(setup setup-2)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (opn (number ?n2)(setup setup-2))
  (not (opn (number ?n3)(setup setup-2)))
  (not (opn (number ?n4)(setup setup-2)))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
  (if (subsetp (create$ ?n2)(create$ ?*sequence-setup-2-feature-cluster*))
  then
  (bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

(defrule MAIN::sequence-setup-2-feature-cluster-9
  (declare (salience 82))
  ?f1<- (opn (number ?n1)(setup setup-2)(preceding_opn ?n2 ?n3 ?n4))
  (test (and (not (= ?n2 ?n3))(not (= ?n2 ?n4))(not (= ?n3 ?n4))(not (= ?n2 0)) (not (= ?n3
0))(not (= ?n4 0))))
  (not (opn (number ?n2)(setup setup-2)))
  (not (opn (number ?n3)(setup setup-2)))
  (not (opn (number ?n4)(setup setup-2)))
  => (bind ?opn-setup-2-cluster (fact-slot-value ?f1 number))
  (bind ?*sequence-setup-2-feature-cluster*(create$ ?*sequence-setup-2-feature-cluster*
?opn-setup-2-cluster))

```

```
(defrule report-sequence-setup-2
=> (printout sequence_setup-2 ?*sequence-setup-2-feature-cluster*)
    (close sequence_setup-2)
    (printout t "The sequence of operations in setup-2 is" ?*sequence-setup-2-feature-cluster*
    crlf)
    (assert (The sequence of operations for setup-2 is operation_numbers ?*sequence-setup-2-
    feature-cluster*)))
```

**;;;The following functions are used to return the identifier of the face for selecting primary  
;;;datum**

```
(deffunction MAIN::area-of-face (?f1)
    (bind ?l (fact-slot-value ?f1 face_length))(bind ?b (fact-slot-value ?f1 face_breadth))
    (bind ?a (* ?l ?b))(return ?a)
```

```
(defglobal ?*largest-area-for-primary-datum* = 0
    ?*face-having-largest-area-for-primary-datum* = 0)
```

```
(deffunction MAIN::largest-area-for-primary-datum (?f1)
    (bind ?a1 (area-of-face ?f1))
    (if(> ?*largest-area-for-primary-datum* ?a1)
    then(bind ?*largest-area-for-primary-datum* ?*largest-area-for-primary-datum*)
    else(bind ?*largest-area-for-primary-datum* ?a1))
    (return ?*largest-area-for-primary-datum*))
```

```
(deffunction MAIN::face-having-largest-area-for-primary-datum (?f1)
    (bind ?a1 (area-of-face ?f1))
    (bind ?n1(fact-slot-value ?f1 number))
    (if(> ?*largest-area-for-primary-datum* ?a1)
    then(bind ?*face-having-largest-area-for-primary-datum* ?*face-having-largest-area-for-
    primary-datum*)
    else(bind ?*face-having-largest-area-for-primary-datum* ?n1))
    (return ?*face-having-largest-area-for-primary-datum*))
```

**;;;The following functions are used to return the identifier of the face for selecting secondary  
;;;datum**

```
(defglobal ?*largest-area-for-secondary-datum* = 0
    ?*face-having-largest-area-for-secondary-datum* = 0)
```

```
(deffunction MAIN::largest-area-for-secondary-datum (?f1)
    (bind ?a1 (area-of-face ?f1))
    (if (> ?*largest-area-for-secondary-datum* ?a1)
    then(bind ?*largest-area-for-secondary-datum* ?*largest-area-for-secondary-datum*)
    else(bind ?*largest-area-for-secondary-datum* ?a1))
    (return ?*largest-area-for-secondary-datum*))
```

```
(deffunction MAIN::face-having-largest-area-for-secondary-datum (?f1)
    (bind ?a1 (area-of-face ?f1))
    (bind ?n1(fact-slot-value ?f1 number))
    (if (> ?*largest-area-for-secondary-datum* ?a1)
    then(bind ?*face-having-largest-area-for-secondary-datum*
    ?*face-having-largest-area-for- secondary-datum*)
    else(bind ?*face-having-largest-area-for-secondary-datum* ?n1))
    (return ?*face-having-largest-area-for-secondary-datum*))
```

**;;;The following functions are used to return the identifier of the face for selecting tertiary datum**

```

;;;datum
(defglobal ?*largest-area-for-tertiary-datum* = 0
          ?*face-having-largest-area-for-tertiary-datum* = 0)

(defun MAIN::largest-area-for-tertiary-datum (?f1)
  (bind ?a1 (area-of-face ?f1))
  (if (> ?*largest-area-for-tertiary-datum* ?a1)
      then(bind ?*largest-area-for-tertiary-datum* ?*largest-area-for-tertiary-datum*)
          else(bind ?*largest-area-for-tertiary-datum* ?a1))
      (return ?*largest-area-for-tertiary-datum*))

(defun MAIN::face-having-largest-area-for-tertiary-datum (?f1)
  (bind ?a1 (area-of-face ?f1))
  (bind ?n1 (fact-slot-value ?f1 number))
  (if (> ?*largest-area-for-tertiary-datum* ?a1)
      then(bind ?*face-having-largest-area-for-tertiary-datum*
                ?*face-having-largest-area-for-tertiary-datum*)
          else(bind ?*face-having-largest-area-for-tertiary-datum* ?n1))
      (return ?*face-having-largest-area-for-tertiary-datum*))

```

**;;; \* RULES FOR SELECTING DATUM \***

```

(defrule MAIN::face-area
  (declare (salience 70))
  ?f1<- (feature(name FACE))
  => (area-of-face ?f1))

```

**;;; Rules for selecting primary datum for setup-1**

```

(defrule MAIN::face-having-largest-area-for-primary-datum-for-setup-1
  (declare (salience 60))
  ?f1<- (feature(name FACE)(number ?number)(TAD AD-3))
  => (largest-area-for-primary-datum ?f1)
      (face-having-largest-area-for-primary-datum ?f1))

(defrule MAIN::selecting-primary-datum-for-setup-1
  (declare (salience 50))
  ?f1<-(feature(name FACE)(number ?number)(TAD AD-3))
  (operation (number ?numero)(on_feature ?number)(TAD AD-3))
  (opn (number ?numero))
  => (if (= ?number ?*face-having-largest-area-for-primary-datum*)
      then (duplicate ?f1 (name PRIMARY-DATUM-SETUP-1)))

```

**;;; Rules for selecting primary datum for setup-2**

```

(defrule MAIN::face-having-largest-area-for-primary-datum-for-setup-2
  (declare (salience 40))
  ?f1<- (feature(name FACE)(number ?number)(TAD AD-6))
  => (largest-area-for-primary-datum ?f1)
      (face-having-largest-area-for-primary-datum ?f1))

(defrule MAIN::selecting-primary-datum-for-setup-2
  (declare (salience 30))
  ?f1<-(feature(name FACE)(number ?number)(TAD AD-6))
  (operation (number ?numero)(on_feature ?number)(TAD AD-6))

```

```
(opn (number ?numero))  
=> (if (= ?number ?*face-having-largest-area-for-primary-datum*)  
    then (duplicate ?f1 (name PRIMARY-DATUM-SETUP-2)))
```

### ;;; Rules for selecting secondary datum for setup-1

```
(defrule MAIN::face-having-largest-area-for-secondary-datum-setup-1  
  (declare (salience 20))  
  ?f1<- (feature(name FACE)(number ?number)(perp_to $? ?N1 $?))  
=> (if (= ?N1 ?*face-having-largest-area-for-primary-datum*)  
    then (and (largest-area-for-secondary-datum ?f1)  
              (face-having-largest-area-for-secondary-datum ?f1))))  
(defrule MAIN::selecting-secondary-datum-for-setup-1  
  (declare (salience 10))  
  (feature(name PRIMARY-DATUM-SETUP-1)(number ?number1))  
  ?f1<-(feature(name FACE)(number ?number2)(perp_to $? ?number1 $?))  
=> (if (= ?number2 ?*face-having-largest-area-for-secondary-datum*)  
    then (duplicate ?f1 (name SECY-DATUM-SETUP-1))))
```

### ;;; Rules for selecting secondary datum for setup-2

```
(defrule MAIN::face-having-largest-area-for-secondary-datum-setup-2  
  (declare (salience 20))  
  ?f1<- (feature(name FACE)(number ?number)(perp_to $? ?N1 $?))  
=> (if (= ?N1 ?*face-having-largest-area-for-primary-datum*)  
    then (and (largest-area-for-secondary-datum ?f1)  
              (face-having-largest-area-for-secondary-datum ?f1))))  
(defrule MAIN::selecting-secondary-datum-for-setup-2  
  (declare (salience 10))  
  (feature(name PRIMARY-DATUM-SETUP-2)(number ?number1))  
  ?f1<-(feature(name FACE)(number ?number2)(perp_to $? ?number1 $?))  
=> (if (= ?number2 ?*face-having-largest-area-for-secondary-datum*)  
    then (duplicate ?f1 (name SECY-DATUM-SETUP-2))))
```

### ;;; Rules for selecting tertiary datum for setup-1

```
(defrule MAIN::face-having-largest-area-for-tertiary-datum-setup-1  
  (declare (salience 9))  
  ?f1<- (feature(name FACE)(number ?number)(perp_to $? ?N1 $? ?N2 $?))  
=> (if (and (= ?N1 ?*face-having-largest-area-for-primary-datum*)  
          (= ?N2 ?*face-having-largest-area-for-secondary-datum*))  
    then (and (largest-area-for-tertiary-datum ?f1)  
              (face-having-largest-area-for-tertiary-datum ?f1))))  
(defrule MAIN::selecting-tertiary-datum-for-setup-1  
  (declare (salience 8))  
  (feature(name PRIMARY-DATUM-SETUP-1)(number ?number1))  
  (feature(name SECY-DATUM-SETUP-1)(number ?number2))  
  ?f1<-(feature(name FACE)(number ?number3)(perp_to $? ?number1 $? ?number2 $?))  
=> (if (= ?number3 ?*face-having-largest-area-for-tertiary-datum*)  
    then (duplicate ?f1 (name TERTIARY-DATUM-SETUP-1))))
```

**::: Rules for selecting tertiary datum for setup-2**

```

(defrule MAIN::face-having-largest-area-for-tertiary-datum-setup-2
  (declare (salience 9))
  ?f1<- (feature(name FACE)(number ?number)(perp_to $? ?N1 $? ?N2 $?))
=> (if (and (= ?N1 ?*face-having-largest-area-for-primary-datum*)
            (= ?N2 ?*face-having-largest-area-for-secondary-datum*))
      then (and (largest-area-for-tertiary-datum ?f1)
                (face-having-largest-area-for-tertiary-datum ?f1))))
(defrule MAIN::selecting-tertiary-datum-for-setup-2
  (declare (salience 8))
  (feature(name PRIMARY-DATUM-SETUP-2)(number ?number1))
  (feature(name SECY-DATUM-SETUP-2)(number ?number2))
  ?f1<-(feature(name FACE)(number ?number3)(perp_to $? ?number1 $? ?number2 $?))
=> (if (= ?number3 ?*face-having-largest-area-for-tertiary-datum*)
      then (duplicate ?f1 (name TERTIARY-DATUM-SETUP-2)))

```

**::: \* RULES FOR SETUP SEQUENCING \***

```

(defrule MAIN::setup_sequencing-1
  (setup-1_feature_cluster (operation_numbers $? ?n1 $?))
  (setup-2_feature_cluster (operation_numbers $? ?n2 $?))
  (operation_precedence (values ?n1 ?n2))
=> (assert (setup_sequence setup-1_feature_cluster setup-2_feature_cluster)))

(defrule MAIN::setup_sequencing-2
  (setup-2_feature_cluster (operation_numbers $? ?n1 $?))
  (setup-1_feature_cluster (operation_numbers $? ?n2 $?))
  (operation_precedence (values ?n1 ?n2))
=> (assert (setup_sequence setup-2_feature_cluster setup-1_feature_cluster)))

```

**::: \* FEATURE AND OPERATION FACTS FOR EXAMPLE PART 1 \***

```

(deffacts MAIN::features_list

(feature(number 1)(name FACE)(type EXTERNAL)(subtype PRIMARY)
(face_length 10)(face_breadth 8)(adjacent_features 3 6 8)
(adjacent_features_names SLOT CHAMFER HOLE )(TAD AD-6))
(feature(number 2)(name FACE)(type EXTERNAL)(subtype PRIMARY)
(face_length 10)(face_breadth 8)(adjacent_features 5)
(adjacent_features_names SLOT )(TAD AD-3))
(feature(number 3)(name SLOT)(type EXTERNAL)(subtype SECONDARY)
(secondary_to 1)(adjacent_features 1)
(adjacent_features_names FACE)(TAD AD-2 AD-5 AD-6))
(feature(number 4)(name STEP)(type EXTERNAL)(subtype SECONDARY)
(secondary_to 1)(adjacent_features 1)
(adjacent_features_names FACE)(TAD AD-2 AD-5 AD-6))
(feature(number 5)(name STEP)(type EXTERNAL)(subtype SECONDARY)
(secondary_to 2)(adjacent_features 2)
(adjacent_features_names FACE)(TAD AD-1 AD-2 AD-3 AD-5))
(feature(number 6)(name CHAMFER)(type EXTERNAL)(subtype SECONDARY)
(secondary_to 7)(adjacent_features 7)
(adjacent_features_names HOLE)(TAD AD-6))
(feature(number 7)(name HOLE)(type INTERNAL)(subtype SECONDARY)
(secondary_to 1)(adjacent_features 1)
(adjacent_features_names FACE)(TAD AD-6))
(feature(number 8)(name HOLE)(type INTERNAL)(subtype SECONDARY)

```

```
(secondary_to 1)(adjacent_features 1)
(adjacent_features_names FACE)(TAD AD-3 AD-6))
```

```
(deffacts MAIN::machining_operations
```

```
(operation(number 101)(type mill)(on_feature 1)(TAD AD-6)(tool end-mill))
(operation(number 102)(type mill)(on_feature 2)(TAD AD-3)(tool end-mill))
(operation(number 201)(type mill)(on_feature 3)(TAD AD-2 AD-5 AD-6)(tool square-end-mill))
(operation(number 501)(type mill)(on_feature 4)(TAD AD-2 AD-5 AD-6)(tool square-end-mill))
(operation(number 502)(type mill)(on_feature 5)(TAD AD-1 AD-2 AD-3 AD-5)
(tool square-end-mill))
(operation(number 400)(type chamfer)(on_feature 6)(TAD AD-6)(tool chamfer-tool))
(operation(number 301)(type drill)(on_feature 7)(TAD AD-6)(tool drill))
(operation(number 302)(type drill)(on_feature 8)(TAD AD-3 AD-6)(tool drill)
(relation_with_feature 2 7)(tolerance 0.20 0.15))
```

---

---

## Publications from the Present Thesis

1. M. Hazarika, S. Deb and D. K. Biswal, An Expert System Based Computer-Aided Process Planning Methodology for Setup Planning of Machined Prismatic Parts, Competitive Manufacturing–Proceedings of the 2nd International & 23rd AIMTDR Conference, pp. 1049–1054, 2008, IIT Madras, Chennai.
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