THESIS REPORT

Ph.D.

Automated Manufacturability Analysis of Machined Parts

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Ph.D. 95-3



Sponsored by the National Science Foundation Engineering Research Center Program, the University of Maryland, Harvard University, and Industry

Abstract

Title of Dissertation: Automated Manufacturability Analysis of

Machined Parts

Satyandra K. Gupta, Doctor of Philosophy, 1994

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Because of pressing demands to reduce lead time and product cost, increasing research attention is being given to integration of engineering design and manufacturing. In this thesis, a systematic approach has been developed for computer-aided manufacturability analysis of machined parts. This approach can be used during design stages to improve the product quality from the manufacturing point of view.

Evaluating the manufacturability of a proposed design involves determining whether or not it is manufacturable with a given set of manufacturing operations—and if so, then finding the associated manufacturing efficiency. In this research, the design is represented as a solid model. The tolerance and surface finish information is represented as attributes of various faces of the solid

model. Machining features are used to model the available machining operations. Since there can be several different ways to manufacture a proposed design, this requires considering alternative ways to manufacture it, in order to determine which one best meets the design and manufacturing objectives.

The approach developed in this thesis is based on the systematic exploration of various machining plans. The first step is to identify all machining features which can potentially be used to machine the given design. Using these features, different machining plans are generated. Each time a new plan generated, it is examined to find whether it can produce the desired design tolerances. If a plan is found to be capable of meeting the tolerance specifications, then its rating is computed. If no machining plan can be found that is capable of producing the design, then the design cannot be machined using the given set of machining operations; otherwise, the manufacturability rating of the design is computed. Since various alternative ways of machining the part are considered in this approach, the conclusions about the manufacturability are more realistic compared to the approaches where just one alternative is considered.

It is anticipated that this research will help in speeding up the evaluation of new product designs in order to decide how or whether to manufacture them. Such a capability will be useful in responding quickly to changing demands and opportunities in the marketplace.

Automated Manufacturability Analysis of Machined Parts

by

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Dissertation submitted to the Faculty of the Graduate School of The University of Maryland in partial fulfillment of the requirements for the degree of Doctor of Philosophy

1994

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Dedication

To my parents,
my wife Sanyukta,
and my brother Sarvesh

Acknowledgements

I would like to express my wholehearted thanks to my advisors Drs. Nau and Zhang for their encouragement and guidance throughout this thesis work. Without their direction this endeavor would have not been possible. In addition, I would like to thank Dr. Magrab for his many insightful comments that have been very helpful in carrying out this research. My thanks are also due to my thesis committee members Drs. Anand, Dally, Hendler, and Minis for serving in my thesis committee and offering suggestions for improvements.

I feel especially grateful to my friends Bill, Diganta, Kutluhan, Subrata, and Steve for their help and support.

Last but foremost, I would like express my deep sense of gratitude and indebtedness to my parents, my wife Sanyukta, and my brother Sarvesh for their understanding, moral support, and affection.

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Chapter 1

Introduction

1.1 Background

Increasing competition is challenging the manufacturing industry to bring competitively priced, well-designed and well-manufactured products to market in a timely fashion. Although product design incurs only a small fraction of the total product cost, the decisions made during the design phase determine the significant portion of the product cost, and can be crucial to the success or failure of the product [89, 85]. Since the cost of making essential design changes escalates steeply with time, the ability to make crucial changes during the design phase translates into significant savings over making changes during production run [89]. To achieve this end, increasing research attention is being given to integrating engineering design and manufacturing. These attempts have led to the evolution of the design for manufacturability (DFM) methodology [5]. This methodology involves simultaneously considering design goals and manufacturing constraints in order to identify and alleviate manufacturing problems while the product is being designed, thereby reducing the lead time and improving the

product quality.

The roots of DFM date as far back as World War II [99]. Scarcity of resources, and constant social and political pressure to build better weapons in the shortest possible turnaround time were the main motivating factors behind the tight integration of design and manufacturing activities. Many of the successful weapons of that period were designed by small, integrated, multi-disciplinary teams [99]. However, with the post-World War II era of prosperity and the resultant rapid growth of industry size came the segregation of design and manufacturing departments, which resulted in a sequential product development environment with little attention to DFM. Increasing global competition and desire to reduce lead time led to the rediscovery of DFM in the late seventies. Some of the earliest attempts involved building inter-departmental design teams that consisted of representatives from the design and manufacturing departments. In these design projects, manufacturing engineers participated in the design process from the beginning and made suggestions about possible ways of improving the manufacturability [25, 36]. However, inter-departmental design teams did not always work harmoniously, many management-related problems exist in building and coordinating such teams [61].

In an attempt to increase awareness of manufacturing considerations among designers, leading professional societies have published a number of manufacturability guidelines for a variety of manufacturing processes [62, 8, 86, 5]. These guidelines mainly enumerate the design configurations that pose manufacturability problems, and are mainly intended as training tools in DFM. To practice DFM, the designer needs to carefully study these guidelines and should try to avoid the configuration that result in poor manufacturability.

The availability of low-cost computational power is providing designers with a variety of CAD tools to help increase productivity and reduce time-consuming build-test-redesign iterations. Examples include tools for finite element analysis. mechanism analysis, simulation, and rapid prototyping. The availability of such tools has become a driving force for research in concurrent engineering where various product life-cycle considerations are addressed at the design stage. As the advantages of concurrent engineering are being realized, more and more downstream activities associated with the various manufacturing aspects are being considered during the design phase, and DFM has become an important part of concurrent engineering [5, 89]. On of the primary goals of concurrent engineering is to build an *intelligent CAD* system by embedding manufacturing related information into the CAD systems. These intelligent CAD systems will achieve DFM by performing automated manufacturability analysis which involves analyzing the design for potential manufacturability problems and assessing its manufacturing cost. It is expected that these systems will alleviate the need to memorize and study the manufacturability checklists, therefore allowing the designers to focus on creative aspects of the design process. Moreover, as the manufacturing resources or practices change in an organization, the knowledge bases of these intelligent CAD systems could be updated automatically with least interference with the design activities of the organization.

The pioneering work of Boothroyd and Dewhurst [7] in developing a comprehensive set of Design for Assembly (DFA) guidelines, has resulted in a number of successful computer-aided DFA tools [39, 42]. In contrast, for other manufacturing processes, research attempts have been limited to off-line manufacturability evaluation of designs using rule-based systems that seem to work in case of rela-

tively simple design shapes [84, 32, 79, 40]. The task of manufacturability analysis requires extensive geometric reasoning. Because the closed architecture solid modeling systems of the late eighties did not allow easy access and manipulation of geometric and topological entities, most of the computer-aided DFM tools developed in that period could not do much geometric reasoning. Thus, their capabilities to handle complex design shapes were very limited. However, with the advent of open architecture solid modeling systems [81], it is now possible to do the sophisticated geometric reasoning for manufacturability analysis.

Research in manufacturability analysis is of paramount importance in context of CAD/CAM systems. Any inadvertent error by the designer may prove very expensive in an automated system. For example, if an inadvertent error such as missing a corner radius or putting a very tight surface finish goes undetected during the design stage, the CAM system may later select a very expensive manufacturing operation to achieve that erroneous design attribute. It is anticipated that a systematic methodology for manufacturability analysis will help in identifying these types of manufacturability problems at the design stage, and will give the designer opportunity to correct them.

1.2 Thesis Scope and Problem Statement

The main objective of this thesis is to develop a systematic approach to computer aided manufacturability analysis, that can be used during early design stages to improve product quality from the manufacturing point of view. This research provides the groundwork for the development of a design-analysis tool that allows the designers to build manufacturability into a design through analysis of its

shape, dimensions and tolerances with respect to given manufacturing processes. Such a tool is intended to be similar to other design-analysis tools (such as FEA, mechanism analysis, etc.)—except that this tool analyzes and reports problems with manufacturability.

Manufacturability is the property of a design that characterizes whether or not the design can be manufactured in a given production environment. The manufacturability rating of a design is a measure that reflects the ease (or difficulty) with which the design can be manufactured. The automated manufacturability analysis problem can be defined as follows.

Given a CAD model of the design and a set of manufacturing resources:

- 1. Determine whether or not the design attributes (i.e., its shape, dimensions, tolerances, surface finishes) can be achieved.
- 2. If the design is found to be manufacturable, then determine its manufacturability rating.
- 3. If the design is not manufacturable, then identify the design attributes that pose manufacturability problems.

As is clear from the above definition, the manufacturability of a design is strongly dependent on the manufacturing processes that will be used to create the design. For example, a design that has an ideal shape for casting may not be suitable for machining. The details of any approach to computer-aided manufacturability analysis will be strongly influenced by the type of manufacturing process addressed by the approach. Thus, the first step in developing a computer-aided manufacturability analysis system is to select a domain of man-

ufacturing processes. The focus of this thesis is the design and manufacturing of machined parts.

Machining is one of the most popular manufacturing process. Every day a large number of new products are designed that are manufactured using machining processes. Even for products that are produced using die casting or injection molding, machining is indirectly used to create the products, because the dies and molds that are used to produce those products are machined. Relatively smaller lead times, the ability to produce wide variety of geometric shapes, and high dimensional accuracy make machining an attractive manufacturing process for small batch production environment.

Machining is a process that allows significant flexibility in choosing the details of the plan. The same design can be produced using many different combinations of machining operations. These different plans may vary considerably in terms of their production cost and achievable machining accuracy. Complex interactions among machine tool, cutting tool, fixture, and workpiece quite often make it difficult to select the best plan. Thus, planning for efficient machining requires significant experience and expertize.

The rule-based approach has been successfully used in building manufacturability analysis system in a limited number of manufacturing domains, where a small set of rules can be formulated that directly relate the design attributes to manufacturability. However, in case of machining, besides some basic principles, there are no established guidelines to design for efficient machining. It is very difficult to enumerate a reasonable set of rules that can directly relate the design attributes to machinability. Thus, in case of machining, it appears that showing the existence of a realizable machining plan is the only fool-proof way of doing

the manufacturability analysis. As described in Section 1.3, showing existence of a realizable machining plan that can produce the design to desired specification poses several challenging research issues.

1.3 Research Issues

Automating manufacturability analysis presents us with problems similar to those in the areas of computer-aided diagnosis: if one is going to endow a computer with both engineering knowledge and the power to provide feedback on manufacturability, one must ensure that the system's feedback is sound. Misdiagnosing the manufacturability problems could result in considerable financial losses. A recent article by Petroski presents several case studies in which a error in design analysis softwares resulted in design failures [64].

In the context of manufacturability analysis systems, there are two types of potential errors that may lead to unreliable results. First, if a design has some attribute that is undesirable for the manufacturing domain but the system does not identify this attribute, then problems may arise during manufacturing. Second, if a design has some attribute that is manufacturable, but the system incorrectly identifies this attribute as non manufacturable and assigns a poor rating to the design, then the designer may waste his time on modifying a correct design. Ideally, a reliable design analysis system should not commit any of these types of errors.

Here are some of the research issues that need to be considered in developing a reliable computer-aided manufacturability analysis system for machined parts.

1. Interpreting the Design: In order to determine whether or not there

exists a realizable manufacturing operation to achieve a given design attribute, feasibility checks need to be performed on the parameters of the manufacturing operation. Therefore, the design attributes need to be interpreted in terms of manufacturing operations that will be used to create them. In order to relate the design attributes with manufacturability problems, it is very important to maintain a correspondence between the design attributes and manufacturing operations.

Traditionally, manufacturing features have been used to represent the relationship between design attributes and manufacturing operations. Most existing feature definitions for machining domain use geometric entities such as a collection of faces or a parameterized volume to represent this relationship. These definitions lack several key pieces of information related to the parameters of the machining operation such as its accessibility, cutting tool, dimensional constraints, and so forth. In order to perform manufacturability analysis, the definition of a feature should include information about the relevant parameters that will be used to determine the realizability of the machining operation. For each of the features, there should also be identification procedures that allows identification of various parameters from examination of the design attributes.

2. Existence of Alternative Machining Plans: The manufacturability of a proposed design depends on the existence of a realizable machining plan that can produce the proposed design. Therefore, evaluating manufacturability involves finding a way to machine the proposed design. In general, there may be several alternative interpretations of the design as different collections of machinable features, corresponding to different ways

to machine the part. Determining which of these alternatives is the most preferable requires considering the part's dimensions, tolerances, and surface finishes, along with the availability and capabilities of machine tools and tooling, and fixturability constraints.

Most existing CAD/CAM systems lack any systematic methodology for generating and evaluating alternative interpretations of the part. Many try to generate a single interpretation for a given part—but in order to do accurate manufacturability analysis, alternative machining plans should be examined in a systematic way.

3. Measures of Manufacturability: In many early rule-based DFM systems, qualitative or abstract quantitative measures were used to rate designs for specific manufacturing domains. For example, Ishii et al. [40] rated designs as "poor", "average", "good", or "excellent". Shanker et al. [79] proposed a scheme in which each design attribute was assigned a manufacturability index that ranged from one to two. Such ratings are difficult to interpret, and if the designer is using more than one manufacturability analysis system (for example, one for machining and the other one for assembly), then it becomes very difficult to compare and combine the ratings from the two systems into one overall rating.

Since all manufacturing operations have measurable time and cost, these can be used as an underlying basis to form a suitable manufacturability rating. The ratings based on time or cost figures can easily be combined into a overall rating. Moreover, they present a realistic view of the difficulty in manufacturing a proposed design. This data will also help the management in making make-or-buy decisions.

4. Combinatorial Explosion in Plan Generation: The possibility of combinatorial explosion in generation of machining plans poses a challenging problem. For most complicated parts, generating and evaluating all possible operation sequences can be very expensive computationally. In most of the realistic cases, very few of the possible alternatives will be practically feasible.

For the purpose of manufacturability analysis, one doesn't necessarily need to find an optimal machining sequence. Partially ordered machining operations provide a good basis for the estimation of production time and cost. Quite often a variety of heuristics can be used to discard any machining plan that may pose fixturability problem, cannot achieve tolerances, or results in unusually high cost.

5. Manufacturability of Design Tolerances: Designers specify dimensional tolerances and geometric tolerances on a design to specify the permissible variations from the nominal geometry that will be compatible with the functionality of the design. These tolerances should be analyzed to make sure that these are achievable.

In most of the generative process planning systems, the process capabilities of machining processes are compared with specified tolerances to select the machining process. However, in presence of geometric tolerances, setup sequences play a major role in determining whether or not a specified tolerance is achievable.

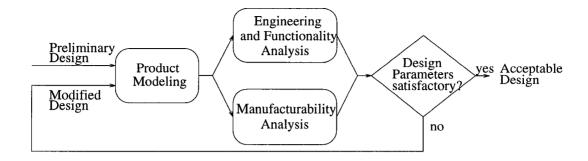


Figure 1.1: Extended design loop.

1.4 Overview of the Research Approach

In a typical CAD environment, the designer creates a design using solid-modeling software, and uses analysis software to examine different aspects of the proposed design's functionality. As shown in Fig. 1.1, in this thesis the design loop has been extended to incorporate a manufacturability analysis system that can be used once the geometry and/or tolerances have been specified. This will help in creating designs that not only satisfy the functional requirements but are also easy to manufacture.

In order to analyze manufacturability, we need information about the proposed design and available manufacturing resources. In this thesis, the nominal geometry of the design is represented as a solid model. The tolerance and surface finish information is represented as attributes of various faces of the solid model. Machining features are used to model the information about the available machining operations—information that includes the process capabilities, dimensional constraints etc.

The basic idea behind the approach developed in this thesis is to generate alternative interpretations of the design as collections of machining features, map these interpretations into machining plans, and evaluate the manufacturability

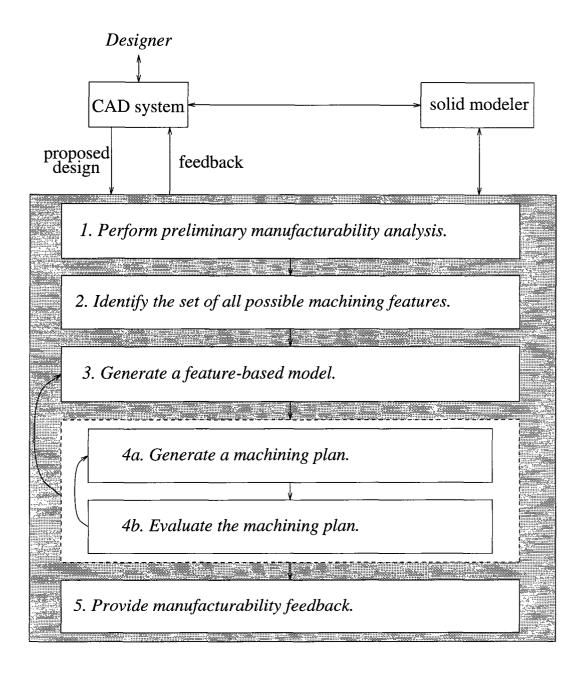


Figure 1.2: Steps in the approach developed in this thesis.

of each machining plans, as described below:

- 1. Perform preliminary manufacturability analysis by identifying any thin sections in the nominal geometry of the design and detecting any redundant or inconsistent tolerances.
- 2. By examining the geometry and topology of various faces of the design that need to be created, generate the set of all machining features that can be used to create the design. Each feature in this set represents a different possible machining operation that can be used to create various surfaces of the part. If this set of features is not sufficient to machine the design completely, then the design is not machinable, so exit with failure. Otherwise, proceed to the next step.
- 3. Do Steps 4(a) and 4(b) repeatedly, until every promising feature-based model (FBM) for the design has been examined (an FBM is a set of machining features that contains no redundant features and is sufficient to create the design, and is generated from the set of machining features identified in Step 2). An FBM is considered unpromising if it is not expected to result in any machining plan better than the ones that have already been examined.
 - 4(a). Generate the set of promising machining plans from the FBM generated in Step 3. Each machining plan represents a partially ordered set of machining operations. A machining plan is considered to be unpromising if it violates any common machining practices.
 - 4(b). Estimate the achievable machining accuracy of each machining plan generated in Step 4(a). This determines which of the machining plans

are capable of producing the design tolerances and surface finishes. Calculate the manufacturability rating of each machining plan that is capable of producing the design tolerances and surface finishes. The manufacturability rating of a machining plan is based on the production time estimates.

5. If one or more machining plans were found during the above steps that are capable of producing the desired tolerances and surface finishes, then the design is machinable, so return the best manufacturability rating. Otherwise, the design is not machinable, so return the set of unmachinable attributes.

The result of this analysis is presented to the designer interactively. For each machinable design attribute, its production time is presented to the designer. This allows the designer to identify the design attributes that are expensive to machine, and take the necessary steps to improve the manufacturability rating of the design. Figure 1.2 graphically presents various steps of the approach developed in this thesis.

There are four cases in which the design will be considered unmachinable. In these cases, the designer will need to consider making changes to the design, as described below:

- 1. If some portions of the design do not correspond to any machining features, then these portions should be modified or eliminated.
- 2. If no machining plan can be found that is capable of creating the design shape and dimensions, then the dimensions and/or shape are unsatisfactory and should be changed so that at least one machining plan works.

- If no machining plan can satisfy the design tolerances, then designer should consider loosening the unachievable tolerances or change the design shape and/or dimensions.
- 4. If there are specified time or cost targets and no machining plan is capable of meeting those targets, then designer should consider changing the design to eliminate those design characteristics that require expensive or time-consuming machining operations.

The approach presented above can also be used incrementally as a design evolves. In particular, the steps that involve machining planning (without estimating machining accuracy) can be used to analyze the design shape and dimensions of the design. After design tolerances have been specified, the steps involving estimation of machining accuracy can be used to analyze the design tolerances.

A proof-of-concept implementation called IMACS (Interactive Manufacturability Analysis and Critiquing System) has been developed to illustrate the approach developed in this thesis. Current capabilities of IMACS are limited to the common machining operations performed on a 3-axis vertical machining center.

It is expected that this research will be useful in providing feedback to the designer about possible manufacturing problems that may arise in trying to meet the specified geometry and tolerances. This will allow the designers to correct the manufacturing problems during the design stage, thereby producing the designs that will be easier to manufacture.

1.5 Organization of Thesis

There are eleven chapters in this thesis. The contents of each chapter are summarized below.

Chapter 2 presents a review of existing literature in related areas. The first section in this chapter describes existing approaches to the computer aided manufacturability analysis. The next two sections in this chapter describe various approaches to the task of design interpretation and generative process planning. The last section discusses limitations of existing approaches.

Chapter 3 describes the schemes for representing the design and machining operations. The first section in this chapter describes a scheme for representing the nominal geometry and tolerances. The second section describes the machining features and how these features can be used to model various machining operations.

Chapter 4 deals with the steps involved with preliminary manufacturability analysis. The first section describes a procedure for detecting the thin sections in the nominal geometry of the design. The second section describes the steps involved in detecting redundant and inconsistent tolerances.

Chapter 5 deals with the steps involved in design interpretation. The first section in this chapter presents an overview of a general feature identification procedure. The next three sections describe the procedures for identifying features corresponding to drilling, end-milling, face-milling and side-milling operations. The last section presents a detailed example.

Chapter 6 deals with the steps involved in generation of feature-based models. The first section in this chapter presents the definition of feature-based models (FBMs). The second section gives an overview of the FBM generation

procedure. The subsequent sections describe details of the various steps of the FBM generation procedure.

Chapter 7 deals with the steps involved in generation of machining plans. The first section in this chapter describes various types of precedence constraints. The second section gives an overview of the plan generation procedure. The subsequent sections describe details of the various steps of the plan generation procedure.

Chapter 8 deals with the steps involved in evaluation of machining plans. The first section describes the procedure for comparing the achievable machining accuracy with design tolerances. The next section describes the procedure for rating the machining plan.

Chapter 9 deals with the steps involved in providing the manufacturability feedback about the design. The first section defines the manufacturability rating. The next two sections describe the feedback information in case of machinable and unmachinable designs.

Chapter 10 describes a prototype system called IMACS that has been developed using the approach developed in this thesis. This chapter also presents two examples to demonstrate the current capabilities of IMACS and the significance of this research.

Chapter 11 summarizes the main research accomplishments of this thesis and describes the anticipated impact. This chapter is concluded by identifying directions for future research.

Chapter 2

Review of Related Research Work

This chapter presents a summary of previous research work in the areas related to the topic of this thesis. In past, a number of software tools have been developed to help designers in evaluating the designs for different types of manufacturing applications. Section 2.1 describes the previous research efforts in the area of automated manufacturability analysis. As described in Chapter 1, the approach presented in this thesis involves automated generation and evaluation of machining plans form CAD models. There is a large body of literature in the area of design interpretation and automated process planning that is related to various steps of the approach presented in this thesis. Section 2.2 describes previous research efforts in the area of design interpretation for manufacturing applications. Section 2.3 describes previous research efforts in the area of generative process planning. Section 2.4 presents a critical appraisal of the previous research and its applicability to manufacturability analysis of machined parts.

2.1 Automated Manufacturability Analysis

2.1.1 Overview

Traditionally, the design process has involved two main activities: synthesis and analysis. Most of the design synthesis activities are currently performed by human designers. Several attempts have been made to automatically synthesize design solutions from functional requirements [6, 83]. However, these attempts are restricted to very narrow domains. Ideally, one would like to have a system which takes customer needs as input and automatically designs a suitable product. However, reality is far from this situation. Currently, there are no general solutions to this kind of design automation problem. So far the most successful pragmatic approach has been to develop tools for critiquing the design as it is being developed in order to guide the human designers in evaluating alternative design considerations. The advent of computers has resulted in a number of design analysis tools. Earlier efforts were focused on building tools for engineering analysis. Currently, research is underway to develop design critiquing and advisory systems for different types of manufacturability issues which need to be addressed in the design phase [38, 42, 80].

Researchers have developed automated manufacturability analysis systems for a wide variety of domains. Most of these systems use rule-based approaches. Design characteristics which improve or degrade the manufacturability are represented as manufacturability rules. These rules are applied to a given design in order to estimate its manufacturability. The subsequent subsections describe various automated manufacturability analysis systems for different types of manufacturing domains.

2.1.2 Assembly

The pioneering work of Boothroyd and Dewhurst [7] in developing the design-for-assembly guidelines has resulted in several automated assembly evaluation and advisory systems. One of the earliest efforts in this direction was made by Jakiela et al. [42]. They integrated a rule-based system with a CAD system to develop a design advisory system. Their system provides a library of predefined features. The designer creates a design by adding the design features from this library. As and when a new feature is added to the design, the system makes use of its production rules to evaluate the design and offers suggestions for improving the design. There are two main limitations with their approach. First, the designer needs to describe the design in terms of features offered by the library. This set of features may not be the most appropriate set of features for the designer. Second, since this system works in an incremental mode, offering advice at every design step, the design improvement suggestions are strongly influenced by the sequence in which the designer enters various features.

Sturges et al. [82] have developed a new assembly evaluation methodology that attempts to overcome some of the limitations of the scheme proposed by Boothroyd and Dewhurst [7]. They have also built a semi-automated evaluation system. Currently, their system has no geometric reasoning capability. It mainly serves as an interactive environment to study the effect of various design configuration on assembly difficulty.

Hsu et al. [39] have developed a new approach to design-for-assembly by examining and evaluating the assembly plans. Their approach involves evaluating the assembly plans using three criteria: parallelism, assemblability, and redundancy. If possible, a better assembly plan is created by modifying the plan. If a

better plan is found, the design is modified by splitting, combining or perturbing various components. Compared to the work Boothroyd and Dewhurst [7], their criteria for evaluating assembly plan is rather restricted. Their approach does not address tolerance or surface finish issues, and can only suggest minor modification to the original design. Moreover, in absence of any model of the functional requirements of the product, the modified product might not satisfy the functional requirements.

2.1.3 Near-Net Shape Manufacturing

Ishii et al. [40] have developed design-compatibility analysis to aid designers in designing the products for various life-cycle considerations. In their approach, for each life-cycle application, a set of design elements is defined. The designer interactively identifies these elements in a proposed design. The designer is also prompted to provide information about user/functional requirements. Their system uses a compatibility knowledge base to evaluate compatibility of various design elements and functional requirements. A compatibility knowledge base is a collection of domain-dependent rules. If a design attribute receives a poor compatibility index, the system offers advice by illustrating predefined cases that result in good compatibility. Ishii and his colleagues have built a number of design advisory systems using this approach. The main strength of these systems is their user-friendly interface. However, this approach has few limitations. First, for domains that involve a large number of design element interactions, this approach would require a large number of rules to correctly identify the compatibility among various design elements. Second, this approach requires the designer to describe the design in terms of predefined design elements, and specify the interaction among various design elements. This is a very tedious job for a designer, and any error in this description may result in incorrect calculation of compatibility index. Finally, it is not clear how this approach will work in domains where a design might have multiple interpretations.

Shanker et al. [79] proposed a generalized methodology to evaluate manufacturability. Their scheme is domain independent and rates the design based on a set of core manufacturability concepts. They describe five core concepts namely, compatibility, complexity, quality, efficiency, and coupling. Based on each of these concepts, they assign a manufacturability index to various attributes of the design. The overall manufacturability of the design is characterized by the sum of the indices for every attribute of the design. Though their methodology addresses some of manufacturability issues, it has a number of limitations. First, since no specific manufacturing process is considered, their approach cannot evaluate whether a given design is manufacturable or not. Second, their approach offers no help in locating the design attributes that pose manufacturability problems.

For net shape manufacturing operations, such as casting, stamping, injection molding, sheet metal working and so forth, several manufacturability evaluation systems have been developed. Most of these systems use rule-based approaches to examine the violation of design-for-manufacturability rules. For example, Lazaro et al. [19] have developed a system for finding violations of design-for-manufacturing rules for sheet-metal parts. Rosen et al. [72] have developed a system for injection molding and die casting.

2.1.4 Machining

Cutkosky and Tenenbaum [17] have developed a system for design and manufacturing of machined parts. Using their system, the designer can create a design by subtracting the machining features from a stock. Their features are volumetric in nature and correspond to machining operations. As a feature is subtracted from the workpiece, the system uses its knowledge base to perform the manufacturability analysis. If any of the manufacturability considerations is violated, the designer is informed about the feature that results in violation. Since this system directly works with the features defined by the designer, it is incumbent upon the designer to describe the design in terms of the most appropriate set of features. Failure to do so may produce incorrect analysis result. In order to select the most appropriate set of features for machining, the designer needs to have good knowledge about machining processes. This requirement significantly limits the scope of this system.

Yannoulakis et al. [93] have developed a manufacturability evaluation system for axi-symmetric parts to be machined on turning centers. They created a feature-based description of the part and evaluated the manufacturability index of each feature. The manufacturability index was based on the estimated machining time of the feature. They employed a number of empirical techniques to estimate cutting parameters and machining time. They did not consider geometric tolerances or the possibility of alternative features in their approach. A number of research issues such as accessibility, precedence constraints, setups, etc., need to be addressed in order to scale up their approach to prismatic parts.

Lu and Subramanyan [84] have developed a manufacturability evaluation system for bearing cages. They addressed several aspects of manufacturability that

included fixturing, tooling, gaging, and material handling. They used multiple cooperative knowledge sources paradigm that separated domain knowledge from the control procedure. However their domain was limited and involved the parts with a limited number of axis-symmetric features.

Priest and Sanchez [69] have developed an empirical method for measuring the manufacturability of machined parts. Their approach involves rating a design based on the producibility rating factors. The producibility rating factor is based on producibility influencing factors and observed production difficulties. They defined producibility rating factors for a variety of manufacturing considerations such as material availability, machinability tooling, material/process risk compatibility etc. Though these ratings reflect difficulty associated with machining, there is no direct correspondence between these ratings and machining cost or time.

Hsiao et al. [37] have developed a knowledge base in order to perform manufacturability analysis of machined parts. Their approach is capable of incorporating user-defined features in manufacturability analysis. They represented the machining process by its elementary machining volume, and limitations of the tool motion. For each of the design feature, they defined the constraint-face sets. The constraint-face sets represent various machining faces and any neighboring faces that restrict the accessibility. They evaluated these constraint-face sets to see if the feature can satisfy the constraints imposed by the elementary machinable volume and the limitations of tool motions of the machining process. Their approach is capable of handling a limited number of accessibility constraints and tolerances.

Anjanappa et al. [4, 48] have developed a rapid prototyping system for

machined parts. The emphasis of their work was on using existing standards and available databases. The design is stored as IGES file, and a rule based feature extractor is used to find machinable features. The set of features is limited and no feature intersection is allowed. The manufacturability analyzer does the analysis based on the specific machining cell configuration for which the system was designed. The manufacturability rating does not find the machining cost and time but matches the features with tools, machines and fixtures. It also lists potentially difficult to manufacture features and non-manufacturable features. It also creates NC machining code for machining of the component. However their system does not investigate the possibility of alternative ways of machining the same part. Overall this work in a useful starting point for detailed investigation of manufacturability analysis.

2.1.5 Electro-Mechanical

O'Grady et al. [61] have developed a constraint-based approach to address various life-cycle considerations during the design of printed wiring boards. They treat the design process as constraint satisfaction problem. Various manufacturability considerations are represented as a constraint network. As designer adds a feature to the design, the constraint network is evaluated for possible violation. If any violation is found, the designer can either select a different manufacturing resources or modify the feature that results in violation. Their approach is computationally intensive. As more features are added to the design, the constraint network grows in size. Their system considers only drilling of holes on printed wiring boards. It is not clear how their approach will handle computational problems in presence of more manufacturing operations.

Harhalakis et al. [32] developed a system for manufacturability evaluation of microwave modules. Their system works with the STEP form feature based representation of the design, and uses rough-cut process plans to assign the manufacturability rating. They use a scale form 1 to 100 to assign the manufacturability ratings. They have compiled these rating by interviewing the machinists on the shop floor. Though these ratings reflect difficulty associated with manufacturing, there is no direct correspondence between these ratings and manufacturing cost or time. Since this work was restricted to flat parts that were rather simple to machine, effects of precedence constraints, tool changes, setup costs, and so forth, were not considered.

2.2 Design Interpretation for DFM and CAM Applications

2.2.1 Overview

In most of the present generation of CAD systems, the design is represented as a solid model that uses low-level geometric information to represent the design. This information cannot be used for manufacturing applications directly. For most of the DFM/CAM applications, the design needs to be interpreted in terms of features that relate design attributes to manufacturing operations.

There have been numerous attempts to define machining features. Section 2.2.2 describes previous efforts in definition and categorization of machining features. There are primarily two approaches to interpret the design in term of features. The first approach is called *feature-based design*. In this approach, the

design is directly modeled in terms of manufacturing features. Section 2.2.3 describes previous research related to this approach. The second approach is called feature recognition. In this approach, the manufacturing features are recognized by a computer program. Section 2.2.4 describes previous research related to this approach. In many situations, there are more than one ways to interpret the design in terms of manufacturing features. Section 2.2.5 describes previous research that addresses generation of alternative interpretations.

2.2.2 Machining Features

Features are perceived to be a communication medium between the design and manufacturing [77, 67]. Currently, the feature-based characterization of the design is considered vital for data exchange between design and manufacturing. In the research community, features have come to mean different things for different research projects—each adopting their own definitions and types to suit the goals of their particular application. This is understandable, as there does not exist any universal feature set that satisfies requirements of all the application domains.

Historically, the concept of a feature originated in the process planning of machined parts [67]. In most process planning systems, features were used to characterize the volumes or the surfaces machined by various types of machining operations. Over the years, the popularity of features has grown, and they are currently being used in a wide variety of manufacturing applications such as nearnet shape manufacturing, assembly, inspection planning, and, so forth. Each of these applications requires different feature definitions. Pratt [67] presented general requirements for feature definitions for a variety of life-cycle applications.

The remainder of this section focuses on machining features.

Two main types of machining feature definitions were proposed [68]. Some researches believed that the features should be defined as a collection of faces that corresponded to the faces created by the machining operation. A number of researchers disagreed and believed that the features should be defined as a parameterized solid that corresponded to the volume removed by the machining operation. Currently, most of the researchers agree that volumetric features capture the machining operations in much more comprehensive manner [68]. Most of current systems use volumetric machining features.

One of the earliest attempts at categorizing machining features was made by CAM-I [10]. This work attempted to exhaustively enumerate process planning features for machined parts. However, this work lacked any mathematical foundation, did not establish any direct relationship among features and manufacturing operations.

Over the years a number of other attempts have been made to define libraries for volumetric machining features. Kramer [50] has defined the MRSEV feature library for representing machining removal volumes. MRSEVs are volumetric features corresponding to machining operations on 3-axis milling machines. MRSEVs can be defined using EXPRESS (the official STEP information modeling language) and STEP form features. Brooks *et al.* [9] defined another library for their process planning system called XCUT. Gindy [27] presents a feature hierarchy describing the geometric information in a class of form features for process planning.

To this date, the most comprehensive methods to define machining features were developed by Chang [11]. His definition is based on tool shapes and cutting trajectories. Features described in this work are very closely related to machining operations. Vandenbrande and Requicha [87] used a similar scheme to define volumetric machining features that corresponded to the tool swept volume.

The standardization community has been evolving a means for describing generic classes of features for the purposes of data exchange. At present, the standard is still evolving and there is no definitive structure for representing and exchanging all the relevant information. Shah [78] presents an investigation of the STEP (Standard for the Exchange of Product Model Data) form features models.

2.2.3 Feature-Based Design

Historically, feature-based design was considered as an alternative to feature recognition. In this approach, the designer directly models the design in terms of manufacturing features, thus obviates the need for the feature recognition. Prototype systems such as Next-Cut [17] and QTC [11] provided a feature-based design interface in which the part was directly modeled in terms of machining features.

In order to analyze the design for various life-cycle considerations, the design needs to be interpreted in terms of domain dependent features. This requires generation of multiple feature-based descriptions of the same design. The designer cannot be delegated the responsibility of this task because of the following reasons:

1. Manually generating a different feature-based description of the design for each life-cycle application requires considerable efforts by the designer.

Moreover, manual generation of more than one feature-based description

may lead to discrepancies among various descriptions.

2. There are a number of application domains in which the feature-based description is not unique [55, 45]. In order to choose the most appropriate description in these situations, the designer needs to be an expert in the application domain. In most cases, it will be unrealistic to assume that the designer will be an expert in a manufacturing related application.

Thus it is quite evident that in order to generate multiple feature-based descriptions, some form of feature extraction will be needed. However, the concept of feature-based design is quite useful and is currently perceived as an effective medium that allows the designer to design with functional features. It is believed that designing with functional features results in a better user interface, and also provides the opportunity to capture several other important information such as design intent and design rationale [49, 77].

Recently several advanced feature based modeling systems have been developed that allow the designer to design the product in terms of user-definable functional features. Shah et al. [77] have developed the ASU feature testbed, which includes a generic feature mapping shell that allows mapping feature from one application to other. Other such systems are developed by Mantyla et al. [52] and ElMaraghy et al. [22].

2.2.4 Recognizing Features from CAD Models

The feature recognition task involves taking a CAD model and interpreting it in terms of manufacturing features. Over the last fifteen years, several feature recognition systems have been developed. These systems use a wide variety of approaches and address a wide variety of problem domains. Though specific details of various approaches vary considerably, in most cases the feature recognition is done by examining the geometric information in the CAD model and matching it with the local geometric and topological configuration of a specific feature class.

Kyprianou [51] presented the first effort to use a grammatical approach to parse solid models of parts for group coding. Methods based on graph-grammars have been used to both recognize features [65, 73] and translate between differing feature representations [71]. Peters [63] analyzes the combinatorial complexity of graph and grammatical approaches to feature recognition and presents heuristics to reduce it.

The first serious work in the area of feature recognition was based on subgraph matching. The approaches of [18, 44] based on graph algorithms provide an excellent level of computational formality. While they have known algorithmic properties, because of combinatorial difficulties they appear difficult to extend to realistic manufacturing problems. The recent work in [24] describes promising techniques that combat the combinatorial problems by abstracting an approximation of the geometric and topological information in a solid model and finding features in the approximation. Corney and Clark [16, 15] have had success in extending the capabilities of graph-based algorithms to more general $2\frac{1}{2}$ -dimensional parts.

Sakurai [76] emphasized the need to be able to extract some form of userdefined feature types that may arise in specific applications and relates it with graph-based feature recognition. In more recent work, Sakurai and Chin [75] propose an algorithm for recognizing general protrusions and cavities through "spatial decomposition and composition." The method, though able to handle intersecting features, is computationally expensive and difficult to prove free from pathological cases.

In one of the early efforts on feature extraction, Woo [92] proposed a method for finding general depression and protrusion features on a part by decomposing the convex hull of the solid model. The approach had several problems, including being confined to polyhedral models and the existence of certain pathological cases in which the procedure would not converge. The non-convergence of Woo's approach has been solved in recent work by Kim [46, 47]. Kim's approach uses convex volume decompositions to produce alternating sums of volumes and techniques for partitioning the solid to avoid non-convergence. Kim further improved the approach by performing additional mapping of the volumes found to machining features.

The work of Henderson [34] was seminal in employing expert systems on the feature recognition problem and has served as a foundation for AI-based approaches. Henderson has made extensive use of graph-based methodologies: in [26] making use of graph-based algorithms to find protrusion and depression features; in Chuang and Henderson [13] use graph-based pattern matching to find feature patterns from part geometry and topology.

The ability to handle interacting features has become an informal benchmark for feature recognition systems and has been the focus of numerous research efforts. The work of Dong [20] included the formalization of a feature description language and employed frame-based reasoning algorithms to extract machining features for computer aided process planning. Marefat [56] used a novel combination of expert system and hypothesis testing techniques to extract surface

features from polyhedral objects. This work was based on the representation scheme of [44]. While providing insights into the feature interaction problem, the method has the same combinatorial difficulties of [44] and the added costs of an expert system to handle interactions. Additionally, although it is stated to be complete for its domain, it is unclear how it would extend to more complex objects and feature classes while maintaining completeness.

Perhaps the most comprehensive and formal approach to date for recognizing features and handling their interactions has been that of Vandenbrande *et al.* [87]. Their method is capable of coming up with alternative interpretations and is described in the next section.

The absence of a clear formalism for the feature recognition problem has made it difficult to ensure completeness of these approaches. In particular, when features intersect with each other, this changes their topology and geometry in ways not taken into account by most existing feature recognition systems. Hence, it is often unclear what specific classes of parts and feature interactions can be handled by various existing approaches.

2.2.5 Generation of Alternative Interpretations

For machined parts, quite often a part has more than one valid interpretation. For the purpose of manufacturability analysis, it is very important that all the feasible interpretations are considered. This requires that alternative interpretations be generated as different collections of machining features. Most of the early research in feature recognition and process planning ignored this aspect completely, and focused on generation of a single interpretation. Recently, generation of alternative interpretations has begun to receive some research attentions.

tion.

The AMPS process planning system [11] includes a feature refinement step, in which heuristic techniques are used for combining a set of features into a more complex feature if it appears that this will optimize the plan, or splitting a feature that cannot be machined into two or more features that can (hopefully) be machined. Since the techniques are heuristic in nature, it is not entirely clear when alternative interpretations will be produced.

Mantyla et al. [55] proposed the concept of feature relaxation. This concept was developed to support the idea of design by least commitment. The proposed feature relaxation groups are pairs of geometric features which are interchangeable. In this approach, the design defined in terms of relaxed features. During process planning, the set of features is selected that results in minimum number of approach directions. However, this work does not incorporate precedence constraints or tolerances into its reasoning. This approach is restricted to the cases that involve pairs of interchangeable features. The cases in which features can be combined to produce a new features or split into two or more features cannot be handled by this approach.

The recent work of Sakurai and Chin [75] generates alternative features. However, this work does not provide means of grouping these features into feature-based models. Moreover, in some cases this approach generates a very large number of features, and does not provide any means to control the resulting combinatorial difficulties.

Vandenbrande and Requicha [87] have developed a system that combines techniques from artificial intelligence and solid modeling. Their program uses hints or clues to identify potential features in the boundary representation of the part. The system is capable of identifying interacting features (e.g., two intersecting slots). This program also produces alternative features in certain cases. However, this system does not guarantee generating all potential machining features.

The first systematic work in the direction of generation of alternative interpretations was done by Karinthi and Nau [45]. They described an approach for producing alternative interpretations of the same object as different collections of volumetric features as the result of algebraic operations on the features, and a system for generating alternative interpretations by performing these algebraic operations. However, this system cannot be used directly for manufacturability evaluation, due to the following limitations. First, there was no direct relation between these features and machining operations, so some of the interpretations generated by this approach were not feasible from the machining point of view. Second, the algebraic operators were not sufficient to generate all interpretations of interest for machining purposes. Third, this work did not deal with the time-ordering constraints induced by some kinds of feature interactions.

2.3 Generative Process Planning

2.3.1 Overview

Automated process planning is one of the key elements in integrating design and manufacturing [3]. Many attempts have been made to automate process planning of machined parts [58, 11, 3, 88, 9, 31, 17]. Two approaches to computer-aided process planning are traditionally recognized, the *variant approach* and *generative approach*. The variant approach involves retrieving an existing plan for

a similar part and making the necessary modification to the plan for the new part. The generative approach involves generation of process plans by means of decision logics and process knowledge. Usually, the task of process planning involves a number of activities such as selection of machining operations, selection of machine tools, selection of cutting tools, determination of setups and fixtures, selection of cutting parameters, sequencing machining operations etc. Most of these activities are interrelated and cannot be performed independently. Generation of the optimal process plan usually requires several iterations. Though progress has been made in automating each of the individual process planning activities, at present there is no automated process planning system that can perform all the process planning activities automatically and generate the optimal process plan even for a moderately complex part. Subsequent two sections describe the previous research work in the areas of plan generation and evaluation.

2.3.2 Plan Generation

Complete process plan generation is a complex task and requires a large number of steps. This section only deals with the steps that are relevant to manufacturability analysis. For details and literature survey on the complete plan generation steps, readers are referred to [3, 11, 88].

2.3.2.1 Process Selection

The task of process selection involves selecting machining processes for the given part. Most of the existing process planning systems work with a single featurebased interpretation of the part and select machining process for each feature independently. In most cases, the definition of features involves shape and tolerance data.

Process knowledge involves shape producing capability and technological constraints for each of the available machining process. A variety of knowledge representation techniques are used to represent process knowledge. Production rules and frames are the most popular techniques. Production rules involve the notion of condition-action sets, and can be expressed as in the from of IF-THEN rules. XCUT [9] and AMPS [11] use production rules to represent process knowledge. Frames permit representation of both procedural and declarative information in terms of attributes, hierarchical relations with other frames, constraints, and procedures. SIPS [58] and NEXT-Cut [17] use frames to represent process knowledge.

The process selection task is performed by examining the shape and tolerance requirements of an individual feature and selecting the process that is capable of meeting the requirements. Quite often, a feature needs a roughing followed by one or more finishing operations. A backward planning strategy has been successfully used to select multiple operations for the feature. In order to perform backward planning, a preprocess (i.e, an operation that provides the machining preconditions) is defined for each machining process. If a machining process requires no preprocess, then that process is called a terminal process. For example, boring has twist drilling as its preprocess, while center drilling is a terminal process. For a given feature, a machining process is selected that meets the final shape and tolerance requirements. If the selected process is not a terminal process, its preprocess is selected as a predecessor to the process. This step is repeated until the selected process is a terminal process. For example, for

a hole with high surface finish, reaming is selected as the final process. Reaming requires twist dilling as its preprocess. This results in selection of twist drilling. Twist drilling requires center drilling as its preprocess. This results in selection of center-drilling operation. The center-drilling is a terminal process, thus selection stops here. A number of process planing systems such as AMPS [11], SIPS [58] etc. use this technique to perform process selection.

2.3.2.2 Identifying Precedence Constraints

For a given part, the machining operations cannot be necessarily performed in any arbitrary order [30]. A number of geometric and technological constraints require that some operations be performed before or after certain other operations. Most process planning systems only deal with the precedence constraints among finishing and roughing operations of the same features.

AMPS [11] uses heuristic techniques to determine precedence constraints among features. A number of rules based on the machining practices have been defined that are used to determine precedence constraints among the pairs of features. This approach allows strict and loose constraints. Strict constraints cannot be violated. Loose constraints can be violated, but are recommended for ensuring good machining practice. The features in this approach are allowed to have multiple approach directions. Such features may require "OR" type of precedence constraints. However, this approach does not have capability to handle "OR" type of precedence constraints. Thus in some cases, it may result in over-constrainted precedences.

The Machinist system [33] is capable of handling the precedences arising because of setup consideration. In this system, precedences are generated by examining the setup interactions among features. If machining of a feature destroys the precondition for clamping during machining of some other feature, then these two features interact and a precedence constraint exists. Various operation sequences are generated using state-space search techniques. If any operation in the sequence violates fixturing requirements, the sequence is discarded.

Because of its closeness to well-known combinatorial optimization problems, optimization of operation sequences has received significant research attention. A number of systems have been developed that take the precedence constraints as input and find the most optimum operation sequence [66, 12]. However, most of these systems do not have capabilities to automatically generate the complete set of precedence constraints.

2.3.2.3 Fixturability and Setup Planning

To ensure successful machining, each intermediate workpiece shape should be fixturable. This requires considerations of fixturing devices and formulating the conditions that are needed for proper fixturing. Setup planning involves determination of various setups in which the part will be machined. Some advances have been made in automated fixture design [74]. Research in fixture design mainly focuses on designing new fixtures for a given geometry.

The Machinist system [33] incorporates few rules for examining the fixturability in a vise. Such rules are defined for each feature. However, these rules are sufficient to guarantee the fixturability of the intermediate workpiece. Machinist also determines the optimum setup using state-space techniques. However, precedences that arise from tolerance considerations are not addressed by the system. Chang [11] presented the comprehensive conditions for holding the workpiece in a vise. These conditions are based on the intermediate workpiece geometry and sufficient for successfully clamping the workpiece. He also presents an algorithm for setup planning. However, this algorithm is not optimal and in certain cases may generate setup plans that are not optimal.

Yue and Murray [94] presented a comprehensive set of fixturability and clamping conditions for vise clamping, machine table clamping, and frame bolting. These conditions are based on intermediate workpiece geometry and include friction force considerations.

2.3.3 Plan Evaluation

After generating the plan, the next step is to evaluate the plan. Plan evaluation consists of two main steps—verification and rating. Plan verification involves determining whether or not a plan is capable of meeting the design specification. The main research issue in plan verification is determining the achievable machining accuracy and comparing it with the design tolerances and surface finishes. Plan rating involves assigning a merit to the plan. If alternative plans exist, ratings are used to select the best plan. Usually the plan ratings are based on the estimated production time and cost.

2.3.3.1 Estimating Production Cost and Time

Economics plays a very important role in manufacturing planning. Estimation of cost and time has been an integral part of process planning activities [11]. Research on machining economics has produced quantitative models for evaluating times and costs related to machining operations [91]. Various optimization

techniques have been applied to these quantitative models to seek the machining parameters which minimize the variable cost, or maximize the production rate and profit rate [98, 1, 2].

The total production time associated with machining operations consists of two components, the machining time and the auxiliary time. The machining time refers to the portion of production time in which the cutting tool engages in metal removal operation. The auxiliary time refers to the non-cutting portion of the production time. The activities that result in auxiliary time include loading/unloading the part on the machine tool, fixturing/setup, tool changes, and non-cutting movements of cutting tools. In most machining economics models, the auxiliary time is approximated by a fixed fraction of the machining time. In actual practice, the total number of setups, and tool changes influence the auxiliary time considerably. In order to get a good estimation of the production time, the auxiliary activities that form a significant portion of total production time should be accounted separately.

The total cost of a machining operation consists of two components, the fixed cost and the variable cost. The fixed cost mainly consists of depreciation of machining equipment, maintenance disbursements, and administrative expenses. The variable cost consists of the costs which vary in accordance with the level of production activity. Typical examples of variable cost would be the cost related to the machining activities, tooling, and auxiliary activities. The variable cost is directly related to the production cost [98]. Estimating the fixed cost involves the vast amount of information, and is a challenging problem. Currently, in most cost models very simplistic estimates are used to estimate the fixed cost.

The setting of cutting parameters influences the production cost and time.

The optimum setting of cutting parameters results is cost and time savings. The cutting parameters directly affect the machining time, tool life, and machining accuracy. Interaction of these three factors determine the actual production cost of and time. Determining the optimum setting of a cutting parameter that strikes a good balance between these three factors and results in the optimum value of objective function is a challenging task. Very complex models have been developed to compute the optimum setting of cutting parameters [1, 2]. Most of these models are computationally intensive and require large computation time. However, for the purposes of manufacturability analysis, such complex optimization is not needed. Based on the past experiences of metal cutting industries, a large amount of data has been complied that provides the recommendations for selecting the cutting parameters for different tool/workpiece combinations [53]. Quite often these recommendations of cutting parameters can be used to obtain reasonable estimation of manufacturability rating.

2.3.3.2 Estimating Machining Accuracy

Each machining operation creates a feature which has certain geometric variations compared to its nominal geometry. Designers normally give design tolerance specifications on the nominal geometry, to specify how large these variations are allowed to be. To verify whether or not a given process plan will produce the desired design tolerances, one needs to estimate machining accuracy of various machining operations.

Various factors such as deformation of the workpiece and tool, vibration, thermal deformation, inaccuracies of machine tool, etc., affect the machining accuracy. Some of these factors are dependent on the setting of cutting param-

eters. For a limited number of machining processes, mechanistic models have been developed to provide quantitative mappings between the cutting parameters (such as cutting speed, feed, and depth of cut) and machining accuracy (such as surface finish and dimensional accuracy) [96, 97, 88, 59].

Zhang et al. presented [95, 96, 97, 60] a comprehensive method for predicting the machining accuracy of turning and boring operations. Their methodology can be extended to model all machining processes involving single-point cutting tools. They generated the model of topography resulting from the machining process by modeling the relative motion of the workpiece and the cutting tool. From the model of topography, they calculated the achievable tolerances and surface finishes produced by the machining process. Their model involved the cutting parameters and structural dynamics of machine tool. Their model also incorporated the random vibrations resulting from variations in the workpiece hardness.

The mathematical models result in the better estimation of machining accuracy. These models also allow to account for specific characteristics of machine tool and workpiece. However, for complex machining operations that do not involve single-point cutting tools, developing a mathematical model to predict machining accuracy is a very difficult task. In such cases, usually the empirical methods are used. Based on the past experiences of metal cutting industries, a significant amount of data has been published that describes the achievable machining accuracy of various machining processes [11, 8, 86]. This data presents the typical value of machining accuracy for different processes and may not be applicable to a specific machine tool.

2.3.3.3 Tolerance Charting

A tolerance chart is graphical representation of the process sequence which helps in visualizing the influence of the proposed sequence on resulting dimensions and tolerances. Traditionally, the tolerance charts have been used to calculate the operational tolerances and to verify that all operations put together will achieve the desired design tolerances. For each step of the the operation sequence, machining accuracy is estimated and tolerance stack ups are calculated.

Most automated process planning systems do not incorporate automated tolerance charting. Recently, attempts have been made to automate tolerance charting [43, 57]. Current research on computer-aided tolerance charting mainly focuses on calculation of optimum intermediate tolerances. These approaches typically use linear programming techniques to arrive at optimal intermediate tolerances. Even for relatively simple parts, the number of equations involved are very high and significant computation time required to solve these equations. Moreover, these approaches only handle a very limited variety of geometric tolerances.

2.4 Discussion

This section critically analyzes the applicability of previous research work to manufacturability analysis of machined parts. First, the main deficiencies of rule-based approaches are examined. Next, we describe why existing approaches to design interpretation and generative process planning are not suitable for the purposes of automated manufacturability analysis.

As described in Section 2.1, a number of successful manufacturability analy-

sis systems have been developed for near-net shape manufacturing. For near-net shape manufacturing, many manufacturability rules directly involve design geometry, leading to success of rule-based approaches. In most of these systems, the design is described in terms of domain-specific features, and manufacturability rules were used to examine the manufacturability of the features. A similar approach have been used to examine the manufacturability of machined parts. However, this approach has not been successful for machined parts, for the following reasons.

- 1. For machined parts, the feature-based representation is not unique. In order to analyze manufacturability correctly, alternative interpretations need to be considered. This requires some form of feature recognition capable of generating alternative interpretations automatically.
- 2. For machining, most manufacturability rules involve parameters of machining operations, and have no direct relation to the design attributes. Thus, manufacturability rules cannot be applied to design attributes directly. Instead, machining plans needs to be generated and evaluated with respect to manufacturability criteria.
- 3. For machining, quite often machining operations interact, i.e., presence of certain operation affects the manufacturability of some other operations. Exhaustively enumerating all possible interactions results in a very large number of rules. This makes rules-based approaches unattractive for the machining domain.

As an alternative, the approach developed in this thesis involves generation and evaluation of alternative machining plans. As described in Sections 2.2 and

- 2.3, several attempts have been made to develop automated feature recognition and process planning systems for machined parts. However, automated manufacturability analysis has different objectives and requirements. Most previous approaches to feature recognition and process planning cannot be directly used in manufacturability analysis for the following reasons:
 - 1. In most previous research, feature recognition was done separately from process planning. However, this is not appropriate for automated manufacturability analysis for the following reason. Most feature recognition systems work with purely geometric information and identify a single feature-based model. Whenever alternative interpretations are present, in absence of any machining information, these systems make an arbitrary choice among various possible alternative.

In order to perform reliable manufacturability analysis, the design interpretation step should be capable of generating all promising interpretations for the design. In certain cases, there might be very large number of interpretations, making it infeasible to generate all possible interpretations. In such cases, planning information can be used to prune unpromising alternatives. Thus, in order to improve computational efficiency the design interpretation, plan generation, and plan evaluation steps should be integrated.

2. Most existing process planning systems focus on generating the optimum plan for individual features. Most of these systems have very limited capabilities for identifying and accounting for the feature interactions. The manufacturability of a part is significantly affected by interacting features.

In the presence of multiple alternatives, performing elaborate plan optimization is computationally very expensive and may result in a very time consuming analysis. Since most design analysis systems are used in interactive manner, the response time is one of the main concerns. Thus, for automated manufacturability analysis, the plan generation step should focus more on handling the feature interactions in proper manner, rather then performing the elaborate plan optimization for individual features.

3. Most existing automated process planning system have extremely limited capabilities to analyze the manufacturability of design tolerances. Most automated tolerance charting work mainly focuses on computing the optimum intermediate tolerances, and has not been integrated with the process planning systems.

Design tolerances are important aspect of the design and affect the manufacturability significantly. Thus, a manufacturability analysis system should be able to analyze the manufacturability of design tolerance.

In summary, in order to perform reliable automated manufacturability analysis for machined parts, we need a new approach that establishes the manufacturability by examining the machining plans. In most cases, there will be alternative ways of machining a proposed design. Thus, a reliable approach to automated manufacturability analysis should be capable of systematically generating and evaluating the alternative machining plans.

Chapter 3

Representing Design and Machining Operations

In order to perform automated manufacturability analysis, design and available machining operations need to be represented as computer models. Section 3.1 describes the scheme used in this thesis for representing the design. Section 3.2 describes how machining operations are modeled using machining features.

3.1 Design Representation

The designer is required to specify the nominal geometry and tolerance/surface finish specifications for the proposed design and its corresponding stock. Section 3.1.1 describes the scheme used in this thesis for representing the nominal geometry. Section 3.1.2 describes the scheme developed in this thesis for representing the tolerance and surface finish specifications.

3.1.1 Representing Nominal Geometry

There are several techniques for geometric modeling in CAD. These techniques range from wire frame models to solid models. Solid models create the most comprehensive geometric representations of the physical objects [54, 35]. These models can be used for answering geometric questions about the physical objects. In this thesis, the nominal geometry will be represented by solid models. There are a number of schemes for representing the solid models. In this thesis, the boundary representation scheme, in which the solid is represented in terms of the bounding faces, is used.

The designer is allowed to choose a method of his/her choice to create the solid model of the part and the stock. However, the nominal geometry of the part and the stock must satisfy the following two restrictions.

- 1. The solid representing the part must be a subset of the solid representing the stock.
- 2. The part or stock boundaries should not have any free-form or sculptured surfaces.

Throughout this thesis, the following conventions and nomenclature will be used to denote solids and various operations among solids. If R is any solid, then b(R) is the boundary of R, and $\iota(R)$ is the interior of R. Note that $R = \iota(R) \cup b(R)$ and that $\iota(R) \cap b(R) = \emptyset$. If R and R' are solids, then $R \cap^* R'$ is the regularized intersection of R and R', i.e., the closure of $\iota(R) \cap \iota(R')$ [35]. Similarly, $R \cup^* R'$ is the regularized union and $R -^* R'$ is the regularized difference.

A part is the finished component to be produced as a result of a set of machining operations on a piece of stock, i.e., the raw material from which the

part is to be machined. The term workpiece is used to describe any intermediate state between the stock and the part. Let P be a solid representing a part, and S be a solid representing the stock from which P is to be made. Then the delta volume (i.e., the volume to be machined), is the solid $\Delta = S^* P$.

3.1.2 Representing Tolerances and Surface Finishes

Traditionally, designers have used geometric dimensioning and tolerancing to specify the permissible variations in the part geometry that are consistent with its functionality. Currently, there are no formal or mathematical methods for tolerancing. Instead, a set of conventions and symbols are used on engineering drawings. The ANSI Y14.5 M standard [23] provides the guidelines for specifying and interpreting the tolerances.

In order to perform automated manufacturability analysis, a tolerance representation scheme is needed that integrates the tolerance information with the solid model. In this thesis, a scheme has been developed that allows the augmentation of a solid model with the tolerance information. Tolerances are attached to various attributes of the nominal geometry of the part. The boundary representation does not have the explicit representation of all the attributes of interest that a designer might consider for attaching the tolerances. Therefore, the following additional attributes are derived from the boundary representation.

1. **Dimensions.** Dimensions are not explicitly defined in the boundary representation. Only distance and angularity type of dimensions are considered in this thesis. A dimension can be derived from the following information in the boundary representation.

- (a) **Parameters of a face.** For example, the radius of a cylindrical face is same as the radius of the underlying cylindrical surface.
- (b) **Distance between two faces.** For example, the width of a slot can be defined as the distance between the faces that form the side walls for the slot.
- (c) **Angle between two faces.** For example, a chamfer angle can be defined as the angle between the faces forming the chamfer.
- 2. **Datum.** A datum is either a face directly present in the boundary representation, or an auxiliary entity that can be defined as a relationship among two or more faces of the part. For example, the axis of a hole and the mid-plane of a slot can each be used as a datum.

Various tolerances are either directly attached to the faces or are attached to one of the derived attributes as defined above. In this thesis, the following types of tolerances/surface finishes are considered.

- 1. **Dimensional tolerances.** These tolerances are attached to dimension attributes and are defined in terms of upper and lower limits.
- 2. Geometric tolerances. These tolerances are attached to various planar and cylindrical faces of the part and characterize the permissible deviation in the form. Some tolerances of this type may require one or more datum attributes.
- 3. Surface finishes. These are assigned to various faces of the part and characterize the surface finish of the face.

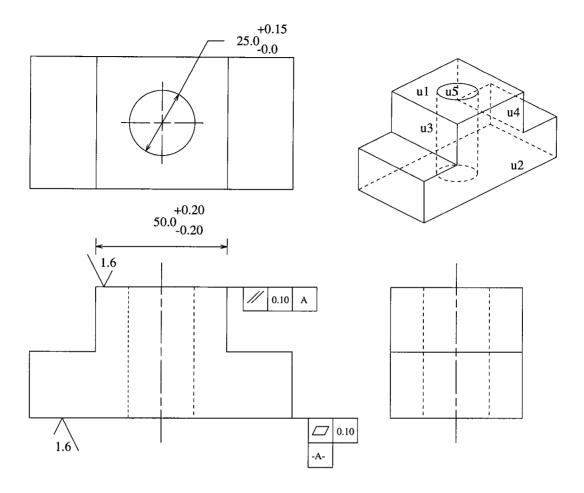


Figure 3.1: Engineering drawing of an example part.

In order to define tolerances on a given solid R, a set of tolerance attribute A_R is defined. Each member of A_R is either a face of R or a dimension attribute of R. Tolerances are attached to each member of A_R . For each type of tolerance, a different class with adequate members is used to represent the relevant information. Tables 3.1, 3.2, and 3.3 present the tolerance representation for the part shown in Figure 3.1.

Table 3.1: Dimensional tolerances for the part shown in Figure 3.1.

dimension	upper limit (mm)	lower limit (mm)
distance between u3 and u4	+0.20	-0.20
dimater of u5	+0.15	-0.00

Table 3.2: Geometric tolerances for the part shown in Figure 3.1.

face	type	material condition	value	datum(s)
u1	parallelism	RFS	0.10	u2
u2	flatness	RFS	0.10	N.A.

Table 3.3: Surface finishes for the part shown in Figure 3.1.

face	surface finish (μm)
u1	1.6
u2	1.6

3.2 Modeling Machining Operations with Machining Features

Machining features are used to relate the design attributes to the machining operations that can be used to create them. Each of the available machining operations is modeled with a machining feature. Every machining feature incorporates necessary information to analyze the realizability of the associated machining operation.

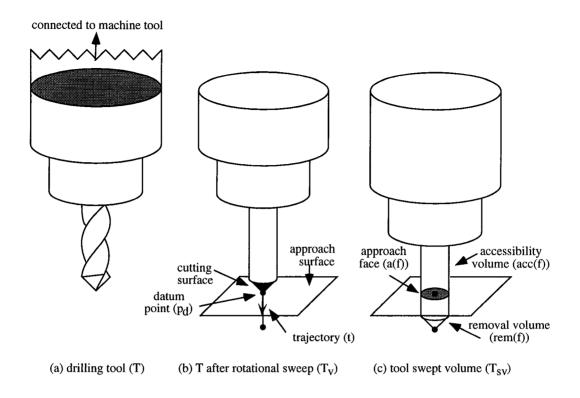


Figure 3.2: A drilling tool, and the resulting swept volume.

3.2.1 Geometric Modeling of Machining Operations

In a machining operation, material is removed by relative motion between the cutting tool and the workpiece. Typically, the cutting tool is mounted on a large machine tool, and the total volume occupied by the cutting tool and the machine tool is quite large. But only a small portion of this total volume, namely the portion that actually gets close to the workpiece, is of interest. This portion is called the *tool volume*, and is denoted by the solid T. Figure 3.2(a) shows a drilling tool. To perform a cutting operation, the tool volume T is given a relative cutting motion with respect to the workpiece. This cutting motion may either be imparted to the tool (examples include various milling operations) or the workpiece (examples include various lathe operations). Most of the time

this relative cutting motion is either linear (operations such as shaping, planning, broaching) or rotational (operations such as turning, drilling, boring, milling). This motion is represented as a sweep s_v , which is either linear or rotational. Let T_v denote the solid generated by applying the sweep s_v to the solid T. For the purpose of locating the tool, a particular point p_d of T_v is selected as the datum point. Figure 3.2(b) shows T_v and p_d for drilling operations. The boundary $b(T_v)$ is naturally partitioned into the following three types of surfaces:

- the separation surface, i.e., the portion of $b(T_v)$ that connects to the machine tool;
- the cutting surface, i.e., the portion of $b(T_v)$ that is capable of cutting the material;
- the non-cutting surface, i.e., the portion of $b(T_v)$ that is not capable of cutting the material.

To perform a machining operation, one sweeps the volume T_v along some cutting trajectory t. A cutting trajectory is defined by a space curve. The trajectory t is feasible only if sweeping T_v along t does not cause interference problems between the non-cutting surface of T_v and the workpiece. Figure 3.2(b) shows an example of a feasible tool trajectory for drilling. If t is feasible, then the solid created by sweeping T_v is $T_{sv} = \{(p - p_d) + q : p \in T \text{ and } q \in t\}$, as shown in Figure 3.2(c).

Let the approach surface π be a surface touching solid T_v and containing T_v to one of its sides. This surface is either planar or cylindrical depending upon the machining operation. For drilling operations this surface is planar as shown in Figure 3.2(b). The side containing T_v is called accessibility side. The other

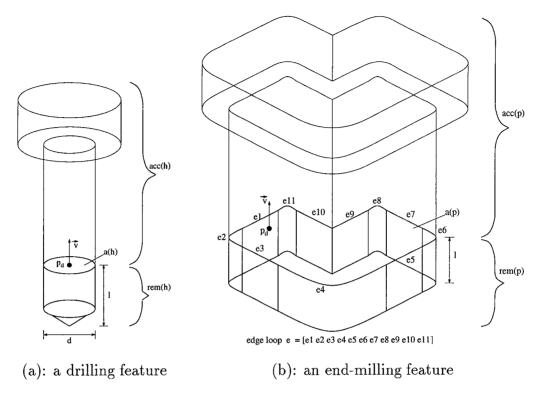


Figure 3.3: Examples of machining features

side is called removal side. The approach surface π partitions T_{sv} into two parts. Only the portion of T_{sv} that lies on the removal side actually corresponds to the volume that can be removed by the machining operation.

3.2.2 Definition of Machining Features

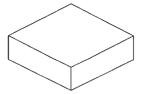
For the purposes of this thesis, a machining feature is the portion of the workpiece affected by a machining operation. However, we will need to know not just the volume of material which the feature can remove from the workpiece, but also what kind of machining operation is being performed, how the workpiece is being accessed in order to perform the operation, and so forth.

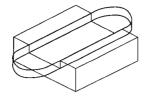
A machining feature f will be created by some machining operation op(f),

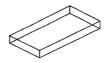
using a cutting tool tool(f). To perform the machining operation, one sweeps the tool along some trajectory that is characterized by some set of parameters param(f). However, only a portion of this swept volume actually corresponds to the volume that can be removed by the machining feature. This volume is called removal volume rem(f). The approach face, $a(f) = \pi \cap T_{sv}$, separates the removal volume from the accessibility volume. The accessibility volume, acc(f), is the remaining portion of the tool swept volume. Below are two examples:

- Suppose we want to drill the hole h shown in Figure 3.3(a). Then op(h) will be drilling. To create h, we will sweep a drilling tool of diameter d along a linear trajectory starting at the datum point p_d and going in along some unit vector \vec{v} for some distance l. Thus, param(h) is the set $\{p_d, \vec{v}, d, l\}$. If the approach face a(h) is as shown in the figure, then the removal volume rem(h) and accessibility volume acc(h) will be as shown in the figure.
- Suppose we want to mill the pocket p shown in Figure 3.3(b). Then op(p) will be end-milling. To create p, we will sweep an end mill of radius r in plane, whose parameters are the starting point p_d , the depth l, the edge-loop e, and the unit orientation vector \vec{v} . Thus, param(p) is the set $\{p_d, \vec{v}, e, l\}$. If the approach face a(p) is as shown in the figure, then the removal volume rem(p) and accessibility volume acc(p) will be as shown in the figure.

Machining features will be referred in terms of the operations used to create them. For example, we say that the hole h is a *drilling feature*, and the pocket p an *end-milling feature*. Usually, we will have only a finite set \mathcal{M} of possible machining operations that can be performed. We will only be interested in







(a): a workpiece

(b): a removal volume,
and its effect on
the workpiece

(c): effective removal
volume with respect
to the workpiece

Figure 3.4: An end-milling feature and its effective removal volume.

machining features that correspond to various operations in \mathcal{M} (i.e., for every feature f of interest, op(f) must be a member of the set \mathcal{M}). Section 3.2.4 describes various types of machining features that correspond to operations on a 3-axis vertical machining center.

Effective Removal Volume. The volume removed by f from a given work-piece W is not necessarily f's removal volume. Instead, it is f's effective removal volume with respect to W, which is defined as $\operatorname{eff}(f,W) = W \cap^* \operatorname{rem}(f)$. Figure 3.4 shows a workpiece, an end-milling feature and its effective removal volume with respect to the workpiece. Whenever the term effective removal volume is used without mention of a specific workpiece, the effective removal volume will be computed with respect to the stock.

Accessibility Condition. A feature f is accessible in a workpiece W, if the accessibility volume of f does not intersect with W (i.e., $acc(f) \cap^* W = \emptyset$). Figure 3.5 shows examples of accessible and inaccessible features.

Approach Condition. A feature f is approachable in a workpiece, if the entry face of f has the proper approach conditions for machining. For example, if

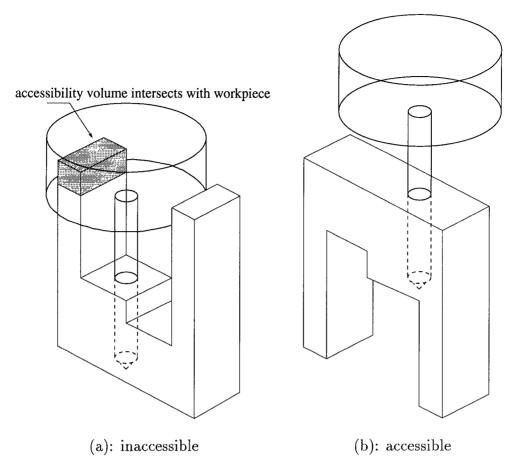


Figure 3.5: Examples of accessibility.

the feature f is a drilling feature, then to ensure proper machining, the entry face of the hole f should be a planar surface perpendicular to the hole axis, and should have a complete circle as its boundary. Figure 3.6 shows examples of approachable and unapproachable features. The drilling feature shown in Figure 3.6(a) is unapproachable because of its curved entry face.

Feature Truncation. A truncated feature f with respect to a solid W is the smallest feature g of f's type and orientation such that g can remove the volume removed by f from W, i.e., eff(g, W) = eff(f, W). An example of feature truncation is shown in Figure 3.7.

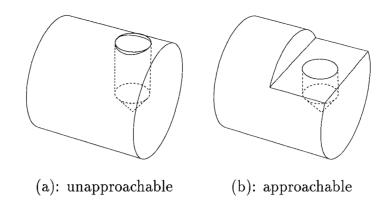


Figure 3.6: Examples of approachability.

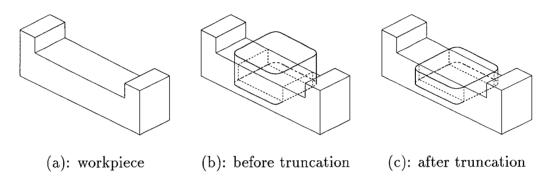


Figure 3.7: An example of feature truncation.

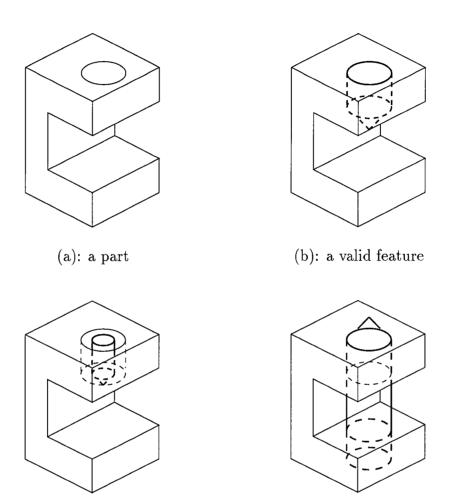
3.2.3 Basic Types of Feature Instances

Only a limited types of feature instances result in proper machining operations. The following types of feature instances are considered in this thesis.

Valid features. A feature f is valid for a given part P, if:

- 1. f creates some portion of the boundary of P (i.e., $b(f) \cap^* b(P) \neq \emptyset$);
- 2. removal volume of f does not intersect with P (i.e., $rem(f) \cap^* P = \emptyset$);
- 3. accessibility volume of f does not intersect with P (i.e., $acc(f) \cap^* P = \emptyset$).

Figure 3.8 shows examples of valid and invalid features.



- (c): an invalid feature, the feature
 does not create any portion of
 the part boundary
- (d): an invalid feature, the feature intersects with the part

Figure 3.8: Examples of valid and invalid features.

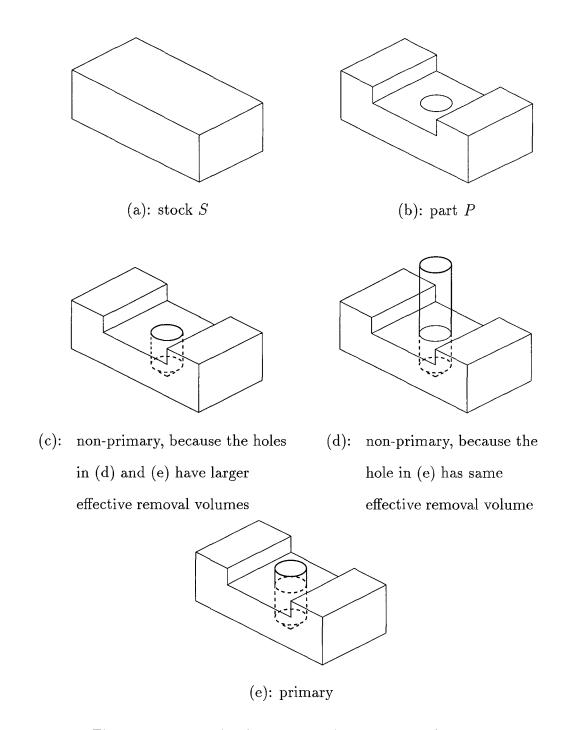


Figure 3.9: Example of primary and non-primary features.

Primary features. A primary feature for a part P and stock S is any valid feature f such that the following conditions are satisfied.

- 1. For every valid feature g (of the same orientation, tool and machining operation as f) whose removal volume contains f's, g has the same effective removal volume as f (i.e., if $\text{rem}(f) \subset \text{rem}(g)$ then eff(g, S) = eff(f, S)).
- 2. For every valid feature g (of the same orientation, tool and machining operation as f) whose removal volume is contained in f's, g has a smaller effective removal volume than f (i.e., if $\text{rem}(g) \subset \text{rem}(f)$ then $\text{eff}(g,S) \subset \text{eff}(f,S)$).

Figure 3.9 shows examples of primary and and non-primary features.

3.2.4 Classification of Feature Types for 3-Axis Vertical Machining Centers

In this thesis, the following types of machining operations and their corresponding features are considered.

- 1. **Drilling.** Drilling operations are used to create holes in the part. Figure 3.10 shows an example of a drilling feature.
- End-Milling. End-milling operations are used to create pockets, slots, steps, notches and grooves. End-milling operations are divided into following two classes.
 - (a) Closed-Pockets. These types of end-milling features can only be accessed from the top face. Figure 3.11(a) shows an example of this type of feature.

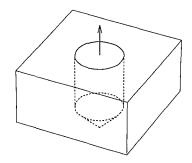


Figure 3.10: A drilling feature.

(b) **Open-Pockets.** These types of end-milling features are accessible from the top and one or more side faces. Examples include steps, slots etc. Figure 3.11(b) shows an example of this type of feature.

End-milling features are characterized by the milling profiles created by the features. Section 3.2.4.1 defines the milling profile and explains the difference between these two types of end-milling features.

- 3. **Face-Milling.** Face-milling is used to create flat surfaces. Figure 3.12 shows an example of a face-milling feature.
- 4. **Side-Milling.** Side-milling is used to create slots that are laterally accessible. There are two types of side milling slots: simple and compound. Figure 3.13 shows examples of side-milling features.

Note that the feature types defined above correspond to roughing operations.

A part might also require finishing operations. If needed, various finishing operations are added during plan generation.

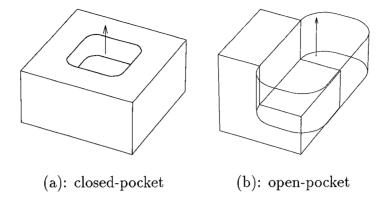


Figure 3.11: End-milling features.

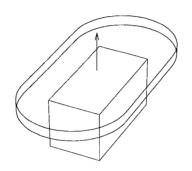


Figure 3.12: A face-milling feature.

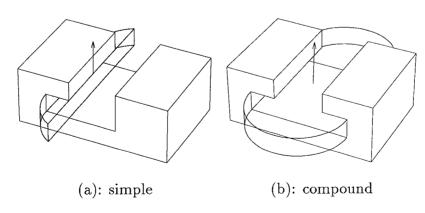


Figure 3.13: Side-milling features.

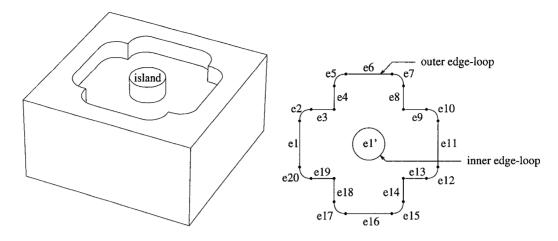
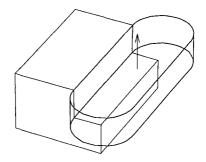


Figure 3.14: An example of a milling profile.

3.2.4.1 Milling Profiles for End-Milling/Face-MillingFeatures

A milling profile is defined by an outer edge-loop, zero or more inner edge-loops, and an orientation vector. An edge-loop is an ordered collection of linear and circular edges lying in a plane. When joined end-to-end, various elements of an edge-loop form a closed, non-self-intersecting, continuous curve. Various inner edge-loops inside the outer edge-loop correspond to various islands in the milling profile. The orientation vector is always perpendicular to the plane containing the edge-loops. Figure 3.14 shows an example of a milling profile. In this example, the ordered collection $\{e1, e2, \ldots, e20\}$ defines the outer loop. This example involves only one inner loop. The ordered collection $\{e1'\}$ defines the inner edge-loop. The convention used in this thesis is to arrange the edges in an edge-loop is as follows. The edges in an outer edge-loop will be arranged in a counter-clockwise manner. Thus, if we are traveling along various edge-loops in the milling profile, the material removed during milling will be to the right side of every edge in the edge-loop.



(a): a milling feature



(b): effective milling profile (c): cross section of the feature Figure 3.15: An example of an effective milling profile.

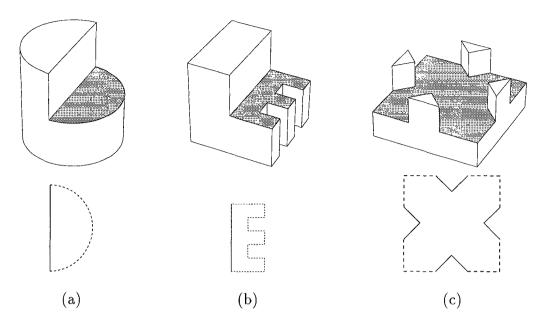


Figure 3.16: Examples of edge classification. The closed edges are drawn with solid lines. The open edges are drawn with dashed lines.

An effective milling profile corresponds to the cross section of the volume removed by the milling operation. Chapter 5 describes how milling features are constructed by identifying the effective milling profiles on the part boundary. In many cases, the cross section of the removal volume of a milling feature will be larger than the effective milling profile created by the feature. In such cases, the profile that corresponds to the cross section of the removal volume of a milling feature is an offset profile created by offsetting the effective milling profile. Figure 3.15 shows an example of a milling feature, where the cross section of a feature is larger than its effective milling profile. Various end/face milling features are characterized by the effective milling profile created by them.

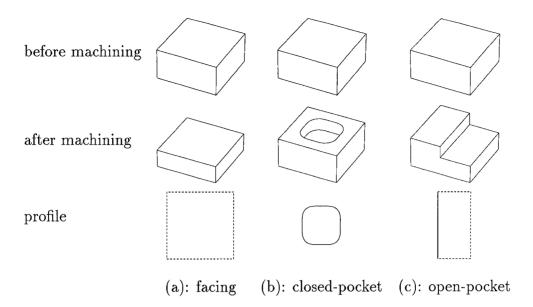


Figure 3.17: Examples of effective milling profile classification. The closed edges are drawn with solid lines. The open edges are drawn with dashed lines.

3.2.4.2 Classification of Edges in an Effective Milling Profile

Various edges in an effective milling profile can be classified as "open" or "closed" edges. Let e be an edge in the profile, and let u be the face formed by sweeping e along the orientation vector of the profile. e is a closed edge if the interior of u intersects with the part boundary. Otherwise, e is an open edge. Figure 3.16 shows three examples of milling profiles along with the edge classification of the profiles.

For the purposes of machining a milling profile, the cutting trajectory should be such that the tool does not cross any closed edge. Crossing a closed edge amounts to gouging into the final part shape and is not permissible. On the other hand, crossing an open edge amounts to tool motion outside the workpiece and is permissible.

3.2.4.3 Classification of Effective Milling Profiles

Depending upon the classification of edges in an effective milling profile, various profiles can be classified in following categories.

- 1. Facing. No closed edge in the profile. Figure 3.17(a) shows an example of a facing profile.
- 2. Closed-Pockets. No open edge in the profile. Figure 3.17(b) shows an example of a closed-pocket profile.
- 3. Open-Pockets. At least one open edge and at least one closed edge in the profile. Figure 3.17(c) shows an example of an open-pocket profile.

Chapter 4

Preliminary Manufacturability

Analysis

Before performing the detailed manufacturability analysis, a preliminary manufacturability analysis is performed. This step corresponds to Step 1 of the overall approach shown in Figure 1.2. This step examines two types of manufacturability problems. First, the portions of the design that may result in thin sections are identified. Section 4.1 describes the procedure developed in this thesis for this task. Second, the redundant or inconsistent tolerances are identified. Section 4.2 describes the procedure developed in this task.

4.1 Detecting Thin Sections

In order to ensure efficient and successful machining, a part should not have any thin sections that might deform during machining and pose problems. For the purpose of this thesis, a section will be considered *thin* if the value of the section thickness is less than the *critical thickness* value. The critical thickness value can be determined by the designer based on the material properties of

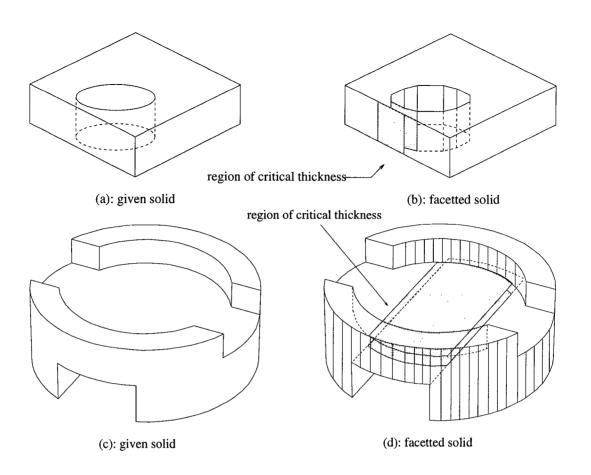


Figure 4.1: Examples of thin sections.

the part, expected machining forces, and maximum permissible static deflection. Machining forces depend on the metal removal rate and can be determined by estimating the maximum allowable metal removal rate on a specific machining center.

Local topology affects the actual stiffness of a thin section. Detecting a thin section merely serves as a warning to the designer. If a design contains a thin section, the designer should use one of the stress-strain analysis methods (such as finite element analysis) to examine the actual extent of manufacturability problem.

In presence of curved faces, detecting thin sections is a difficult task. In this

thesis in order to detect thin sections, curved faces are approximated by planar surfaces. Thin sections are characterized by regions of critical thickness. The region of critical thickness describes the portions of the part boundary where the section thickness is equal or less than the critical section thickness. The following steps are used to determine the regions of critical thickness.

- 1. Facet the solid. This step creates the faceted model of the solid in which the boundary is approximated by planar faces. The desired estimation accuracy determines the faceting accuracy.
- 2. For every pair of facets (y, y') that belong to two different non-touching faces, do the following.
 - (a) Find the half space H defined by the plane containing y, and the inward pointing (inside the material) normal vector of y. Similarly, find the half space H' defined by the plane containing y', and the inward pointing normal vector of y'.
 - (b) Trim all portions of y that lie outside H'. Similarly, trim all portions of y' that lie outside H.
 - (c) If either y or y' has zero area, then there is no region of critical thickness between y and y', so discard this pair.
 - (d) If y and y' are parallel to each other, then do the following.
 - i. Find the distance d between the planes containing y and y'.
 - ii. If $d \leq t_{cr}$ (critical thickness), then do the following.
 - A. Find the projection y_p of y on y'. Similarly, find the projection y'_p of y' on y.

- B. y_p and y'_p define the region of critical thickness between y and y'.
- (e) If y and y' are not parallel to each other, then do the following.
 - i. Find the line l of intersection between the two planes containing y and y'.
 - ii. Trim all portion of y and y' that are more than $t_{cr}/\sin(\alpha)$ distance from l. Here α is the angle between the two planes containing y and y'.
 - iii. If both y and y' have non-zero areas, then do the following.
 - A. Find the projection y_{p1} of y on y' in the direction perpendicular to y'. Find the projection y'_{p1} of y' on y in the direction perpendicular to y.
 - B. Find the projection y_{p2} of y on y' in the direction perpendicular to y. Find the projection y'_{p2} of y' on y in the direction perpendicular to y'.
 - C. Unite y_{p1} and y_{p2} to get y_p . Similarly, unite y'_{p1} and y'_{p2} to get y'_p .
 - D. y_p and y'_p define the region of critical thickness between y and y'.

Figure 4.1 shows two parts with thin sections. This figure also illustrates the regions of critical thickness as determined by above procedure.

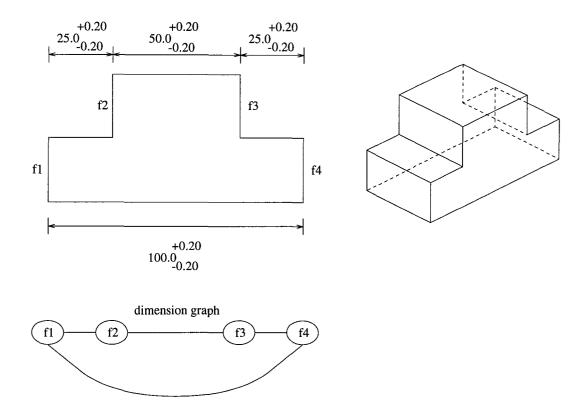


Figure 4.2: Example of inconsistent dimensional tolerances.

4.2 Examining Tolerance Consistency and Redundancy

In order to perform manufacturability analysis correctly, we need to make sure that a design does not have any inconsistent or redundant tolerances. Inconsistency or redundancy in tolerance specifications leads to problems during generation and evaluation of machining plans. In order to avoid these problems, the design tolerances are examined before proceeding with the planning steps. In this thesis, only overspecified length tolerances and redundant form tolerances are examined.

4.2.1 Overspecification of Length Tolerances

In a dimensional chain, all of the length tolerances cannot be specified independently. Typically, a dependent tolerance in a dimensional chain can be determined by an additive rule. If length tolerances have been defined for two independent dimensions, then the tolerance on the sum or the difference of these two dimensions can be determined by using the worst case analysis. Overspecification of dimensional tolerances results in conflicting values of tolerances.

The following two-step procedure is used to examine the possibility of over specified dimensional tolerances.

- 1. Construct a dimension graph in the following manner:
 - (a) for every face of the part that is used to define the dimension for a length tolerance, add a node in the dimension graph;
 - (b) for every length tolerance, add an edge between the two nodes that correspond to the faces defining the underlying dimension.
- 2. If the dimension graph has a cycle, then there are overspecified length tolerances.

If for a proposed design, the above procedure finds overspecified length tolerances, then the designer should consider removing some of the length tolerances to make the dimension graph acyclic.

The example shown in Figure 4.2 has overspecified length tolerances. As illustrated in the figure, the dimension graph for this part has a cycle.

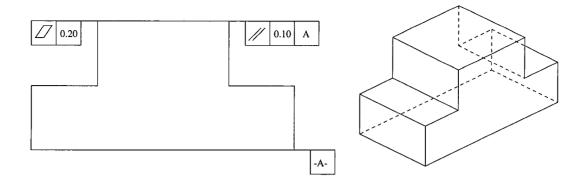


Figure 4.3: Example of redundancy in form tolerances.

4.2.2 Redundancy of Form Tolerances

If two different types of geometric tolerances are specified for a face, then the interaction among these two tolerances might make one of the tolerances redundant. A redundant tolerance can be removed without affecting the functionality of the part. In order to make machining planning efficient, we want to identify and remove all the redundant tolerances. In this thesis, only redundancy of form tolerances is examined.

The condition for redundancy of a form tolerance can be stated as follows. Suppose that a face has been assigned a form tolerance and some other geometric tolerance. The form tolerance for the face will be considered redundant, if the value of the other geometric tolerance is tighter (smaller in numeric value) than the form tolerance.

Figure 4.3 shows an example in which the tighter parallelism tolerance on the top face makes the flatness tolerance redundant.

Chapter 5

Design Interpretation

After performing the preliminary manufacturability analysis, the next step is to interpret the design in terms of machining features. This step corresponds to Step 2 of the overall approach shown in Figure 1.2. Section 5.1 provides an overview of the feature identification approach developed in this thesis. Each type of feature is recognized using a feature-specific identification procedure. Sections 5.2, 5.3, and 5.4 describe feature identification procedures for different types of features.

5.1 Overview of Feature Identification

The problem of identifying the machining features can be defined as follows: given solids representing the part P and the stock S, and a set of machining operations \mathcal{M} , find the set of all features \mathcal{F} that correspond to useful machining operations that can be used to machine P from S. The features in \mathcal{F} will be used to generate machining plans.

Machining features are identified by matching the geometric characteristics of various part faces with various types of features. The boundary of a feature is made up of different types of faces. Each type of face (planar, conical, etc.) may be a part of the boundary of one or more types of features. For example, a cylindrical face could be considered as the side face of a drilling feature and as a corner radius of an end-milling feature. For a given part face, we would like to construct all possible useful feature instances that might be used to create the face. For example, in the case of a cylindrical face, we want to try to instantiate both a drilling feature and an end-milling feature. Any feature instance that intersects with the part is not valid and is discarded.

5.1.1 Primary Feature Set

An arbitrary part and stock may present a problem because they could give rise to an infinite number of instances of valid features, giving rise to an infinitely large feature set. Only those features that are useful for manufacturability analysis will be of interest. Therefore, feature instances satisfying the following restrictions will be identified.

- 1. Only primary feature instances (see Section 3.2.3 for details) will be identified. The volume removed by any machining operation is a subset of some primary feature and can be generated by truncating the primary feature.
- 2. In some cases, a feature type might have infinite possible orientations resulting in an infinite number of feature instances. In such cases, only a finite (polynomial in number of part faces) number of orientations that correspond to realistic machining choices will be tried.

For a given part, the set of features \mathcal{F} that satisfies the above restrictions is called the *primary feature set*. Note that the primary feature set will only

involve polynomial (in number of part faces) number of feature instances.

5.1.2 Procedure to Identify Primary Feature Set

All the part faces that need to be created are considered, and primary features are identified that are capable of creating those faces. The basic idea is given below:

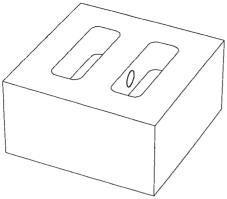
procedure IDENTIFY-FEATURES (P, S)

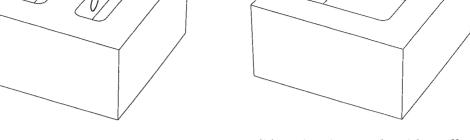
- 1. U := b(P) b(S)
 - (U is the set of all faces of P that are not faces of S. These are the faces of P that will need to be machined.)
- 2. For each face $u \in U$, do the following:

For each machining operation $m \in \mathcal{M}$ that is capable of creating the surface u, do the following:

- (a) Identify every primary feature f such that op(f) = m and f can create u (i.e., u is a subface of some face of f).
- (b) Add f to \mathcal{F} .
- 3. If by subtracting the features in \mathcal{F} from S we do not get P (i.e., $S -^* \cup_{f \in \mathcal{F}} \operatorname{rem}(f) \neq P$), then P is $\operatorname{unmachinable}$.

The above procedure considers all part faces that need to be created and instantiates the primary features capable of covering all or a portion of each face. For each type of face, a procedure is needed that, via queries to the solid modeler, constructs the set of primary features that contain all or part of that





- the hole on the side wall is not machinable
- (b): the slot on the side wall is not machinable

Figure 5.1: Examples of unmachinable parts.

face. Details of these procedures are specific to the feature type and are described in Sections 5.2, 5.3 and 5.4.

In some cases, certain part faces cannot be covered by any machining feature. These type of situations lead to unmachinable part geometry. For example, Figure 5.1 shows some unmachinable parts.

Identifying Drilling Features 5.2

In Step 2(a) of IDENTIFY-FEATURES procedure, a primary drilling feature can be recognized by constructing it from its its conical bottom face or its cylindrical side face. The procedure we use for this task was developed by Regli et al. and is described in [70, 29]. For those reasons the details of the procedure are omitted here, but the basic idea is as follows. If the hole is through (i.e., the conical bottom face is not present in the part boundary), then there are two possible feature instances: one in each direction along the axis of cylindrical face. If the

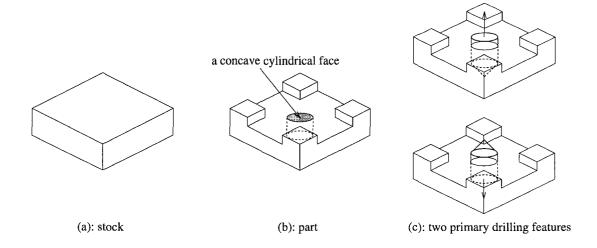


Figure 5.2: Recognizing drilling features.

hole is blind, only one feature instance exists and can be constructed using its conical face.

Figures 5.2(a) and (b) show an example part and stock. As shown in Figure 5.2(b), the part has a concave cylindrical face that can be created by a drilling operation. This face is accessible along both the directions parallel to its axis. Figure 5.2(c) shows two primary drilling features that can be used to create this face.

5.3 Identifying End-Milling and Face-Milling Features

In Step 2(a) of IDENTIFY-FEATURES procedure, a primary end-milling or a primary face-milling feature is recognized as follows. Some of the planar and cylindrical part faces can be created by end-milling operations. Some of the planar part faces can be created by face-milling operations. Face-milling and end-milling features are identified by recognizing the effective milling profiles

in the given part (for details see Section 3.2.4.1). An effective milling profile corresponds to the cross section of the volume removed by the milling operation. The volume removed by the milling operation can be found by sweeping the effective milling profile. Various milling features are based on the tool swept volume. Thus, we are interested in finding the cross section of the tool swept volume. In many cases, the tool swept volume is larger than the volume removed by the milling operations (an example is presented in Section 3.2.4.1), and can be generated by offsetting the effective milling profile. Identification of end/face milling features requires the following steps.

- 1. Identification of effective milling profile. The first step is to examine the part boundary and identify and classify an effective milling profile, as described in Section 5.3.1.
- 2. Selecting the tool size. The tool swept volume depends on the size of the tool. Thus, in order to find a milling feature, the next step is to select a tool of appropriate size. Different types of geometric constraints resulting from the configuration of the profile impose restriction on the tool size. In order to select the most appropriate tool, these constraints need to considered. Section 5.3.2 describes the procedure for estimating the appropriate tool size for different types of effective milling profiles.
- 3. Offsetting the effective milling profile. After selecting the tool of appropriate size, the next step is to offset the effective milling profile. Section 5.3.3 describes the procedure for offsetting the profiles.
- 4. Constructing the milling features. Finally, the milling features are constructed by sweeping the offset profiles. Section 5.3.4 describes the

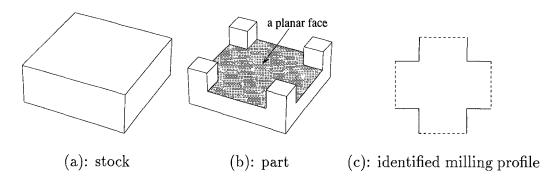


Figure 5.3: Example of identifying a milling profile.

procedure for constructing the removal volume of milling feature.

5.3.1 Identifying Effective Milling Profiles

The procedure we use for this task was developed by Regli et al. and is described in [70, 29]. For those reasons the details of the procedure are omitted here, but the basic idea is as follows. There are two different ways of identifying effective milling profiles. First, the profiles can be identified by the planar bottom face of the milling feature. Second, the profiles can be identified by the side faces of the milled volume. After identifying an effective milling profile, various edges in the profile are classified as open or closed edges (open and closed edges are defined in Section 3.2.4.1). These edges are used to classify the effective milling profile into open-pocket, closed-pocket or facing profile.

Figures 5.3(a) and (b) show an example part and stock. As shown in Figure 5.3(b), the part has a planar face that can be created by a milling operation. Figure 5.3(c) shows the effective milling profile identified from this face. This milling profile has both open and closed edges, therefore this profile is classified as an open-pocket profile.

5.3.2 Selecting the Tool Size

A milling feature is created by sweeping the tool along a cutting trajectory. The length of cutting trajectory depends on the the tool size. To facilitate faster machining, we will be interested in selecting the tool that will require smallest possible cutting trajectory length. In general, a milling feature can be created using multiple milling tools. However in this thesis, we assume that the milling feature will be created by a single milling tool. During estimation of machining time, a suitable correction factor will be used to account for the possibility of multi-cutter milling (details are described in Chapter 8).

In a typical milling operation, larger tool diameter results in shorter trajectory length. However, a variety of constraints resulting from the geometric configuration of the milling profile will restrict the maximum tool size that can be used to create the milling profile. For a given effective milling profile X, a milling tool T will result in the upper bound on the tool size, if for every larger tool T', there exists no cutting trajectory for T' that can create X (i.e., T' cannot create X without crossing closed edges, or intersecting with the part). Note that in many situations, this upper-bound will be infinite. However, after a certain cut-off value, increasing the tool size does not decrease the trajectory length any further. In such situations, this cut-off value along with various machining considerations will be used to determine the upper bound on the tool size.

5.3.2.1 Closed-Pocket/Open-Pocket Profiles

Presence of closed edges in closed-pocket/open-pocket profiles may impose certain restrictions on the maximum tool size that can be used to create the profile. These restrictions can be categorized as follows:

- 1. Curvature of the Concave Closed Edges: In order to sweep a tool along a concave closed edge, the curvature of the tool should be less than the curvature of the edge. Otherwise, the tool cannot be swept along the edge without intersecting the edge. Figure 5.4 shows an example of a closed concave edge in a profile and the resulting restriction on the tool size.
- 2. Narrow Passages: Two closed edges in a profile may form a narrow passage. Sweeping the tool along any of the two closed edges that from a narrow passage will require the tool to pass through the narrow passage. Therefore, the diameter of the tool should not be greater than the width of the passage. Figure 5.5 shows an example of a narrow passage in a profile and the resulting restriction on the tool size.
- 3. Concave Corners: Two adjoining closed edges or two closed edges that are separated by one or more open edges form a corner. If a corner formed by two edges is concave (i.e., tool can simultaneously touch both the edges), then it may impose restrictions on the tool size. Figure 5.6 shows an example of a corner in a profile and the resulting restriction on the tool size.

For any given profile, there is a lower bound on the length of the cutting trajectory. As we increase the tool size, the length of the cutting trajectory starts approaching this value. For any given profile, there is a cut-off value of the tool size that corresponds to the lower bound on the length of cutting trajectory. If we increase the tool size beyond this cut-off value, the length of cutting trajectory will not decrease any further.

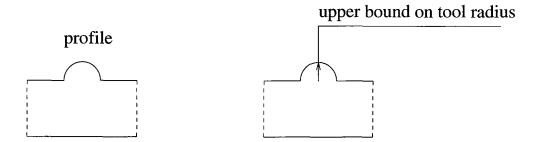


Figure 5.4: A tool-size restriction because of concave curvature of the profile. The closed edges are drawn with solid lines. The open edges are drawn with dashed lines.

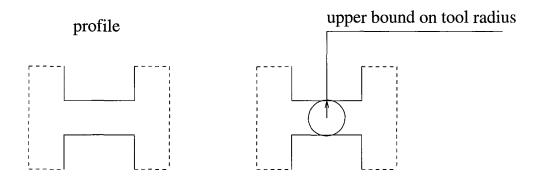


Figure 5.5: A tool-size restriction because of a narrow passage in the profile. The closed edges are drawn with solid lines. The open edges are drawn with dashed lines.

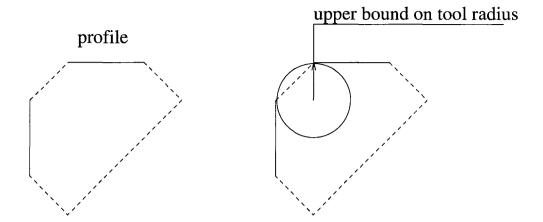


Figure 5.6: A tool-size restriction because of a concave corner in the profile. The closed edges are drawn with solid lines. The open edges are drawn with dashed lines.

For a closed-pocket/open-pocket profile, the upper bound on the tool diameter d_u is defined as follows:

$$d_u = \min(d_{cur}, d_{pas}, d_{cor}, d_{trj}, d_{max})$$

where,

 d_{cur} = upper bound due to curvature,

 d_{pas} = upper bound due to narrow passages,

 d_{cor} = upper bound due to corners,

 d_{trj} = cut-off value due to the lower bound on the trajectory length,

 d_{max} = maximum available tool diameter.

Computing d_{cur} . Linear edges have infinite radius, therefore these edges do not result in any restriction on the tool size. Only concave circular edges result in restriction on the tool size. d_{cur} is calculated as follows.

- 1. If there are no concave circular edges in the profile, then $d_{cur} = d_{max}$.
- 2. Otherwise, let e_{rmin} be the concave circular edge in profile with the minimum radius.

 $d_{cur} = \text{diameter of } e_{rmin}.$

Computing d_{pas} . d_{pas} is computed by examining the potential narrow passages and the constraints imposed by them. The upper bound is determined by the most stringent constraint. The procedure for this task involves following steps:

- 1. Initialize $d_{pas} = d_{max}$.
- 2. For every pair of non adjoining closed edges (e_i, e_j) in the profile, do the following:
 - (a) If e_i and e_j are non-parallel linear edges, then find the line segment l_{min} that results in minimum distance between e_i and e_j .
 - i. If l_{min} does not completely lie inside the profile, then this pair cannot form a narrow passage, so discard this pair.
 - ii. Otherwise,
 - A. Let c be the circle with l_{min} as its diameter. Let l_{min} partition the original profile into two profiles, one on each side of l_{min} .
 - B. If any of the partitioned profile is completely enclosed by c, then the tool will not need to cross l_{min} . Thus, a relaxed constraint can be assigned on the tool diameter. This constraint is calculated as follows. Find the *largest* circle c' such that:
 - I. c' encloses one of the partitioned profile;

- II. c' does not intersect with e_i and e_j ;
- III. c' has l_{min} as its chord.

If $d_{pas} > \text{diameter of } c'$, then $d_{pas} = \text{diameter of } c'$.

C. Otherwise, if $d_{pas} > \text{length of } l_{min}$, then $d_{pas} = \text{length of } l_{min}$.

(b) Otherwise,

- i. Find a line segment l of smallest length such that:
 - A. end points of l lie on e_i and e_j ;
 - B. *l* completely lies inside the profile.
- ii. If no such l can be found, then this pair cannot form a narrow passage, so discard this pair.
- iii. Otherwise, if $d_{pas} > \text{length of } l$, then $d_{pas} = \text{length of } l$.

3. Return d_{pas} .

When a pair of edges involves a circular edge or parallel linear edges, the line segment that results in minimum distance between the two edges in the pair is not defined uniquely. In some cases, there might be infinite number of such line segments. In the case of parallel linear edges, the edge normals are constant, thus the existence of the line segment in Step 2(b) can be easily established. In case of circular edges this computation can be quite complicated. However, for the purposes various computations in Step 2(b), approximation of circular edge by a series of line segments produces satisfactory results.

Computing d_{cor} . d_{cor} is computed by examining the presence of various concave corners in the profile and identifying the resulting restrictions on the tool diameter.

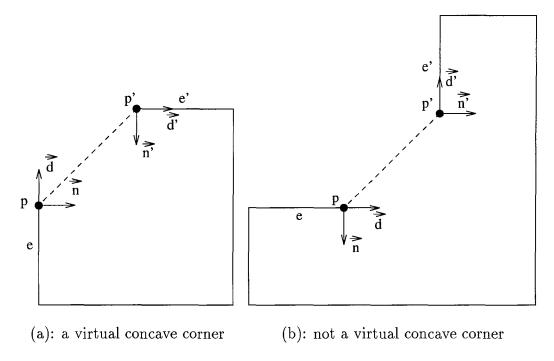


Figure 5.7: Illustration of conditions for virtual corners.

Two adjoining closed edges form a *corner*. Let e and e' be two adjoining closed edges on the profile. e and e' will from a *concave corner*, if the interior angle between e and e' at the point of intersection is less than 180 degrees. In presence of a concave corner in the profile, the upper bound on the tool diameter is assigned to the zero value.

Two edges that are separated by a series of open edges may form a virtual corner. A virtual concave corner is defined as follows. Let e and e' be two closed edges on the profile. Let p and p' be the end points on e and e' that are separated by a series of open edges. Let l be the line segment joining points p and p'. Let q be the interior angle (i.e., measured inside the profile) between q and the tangent of q at q be the interior angle between q and the tangent of q at q will form a virtual concave corner at q and q, if following conditions are satisfied:

- 1. no portion of l lies inside the profile;
- 2. either $90 < \alpha < 180$, or $90 < \alpha' < 180$.

Edge e and e' in Figure 5.7(a) form a virtual concave corner. Edge e and e' in Figure 5.7(b) do not form a virtual concave corner.

The upper bound on the tool diameter resulting from a virtual concave corner is calculated as follows. Let d be the diameter of the circle that has l as its chord and is tangential to e at p. If no such circle exists, then d is defined to be infinity. Similarly, let d' be the diameter of the circle that has l as its chord and is tangential to e' at p'. If no such circle exists, then d' is defined to be infinity. The upper bound resulting from the virtual concave corner is defined to be the smaller of d and d'.

The procedure for computing d_{cor} involves the following steps.

- 1. Initialize $d_{cor} = d_{max}$.
- 2. For every adjoining pair of closed edges (e_i, e_j) , do the following.
 - (a) If e_i and e_j form an concave corner, then $d_{cor} = 0$.
 - (b) Otherwise, discard this pair.
- 3. For every pair of closed edges (e_i, e_j) that are separated by a series of open edges, do the following.
 - (a) If e_i and e_j from a virtual concave corner, then do the following.
 - i. Let d be the upper bound resulting from the virtual concave corner.
 - ii. If $d_{cor} > d$, then $d_{cor} = d$.

- (b) Otherwise, discard this pair.
- 4. Return d_{cor} .

Computing d_{trj} . In order to create closed linear edges and convex circular edges, the tool will have to be swept along the corresponding offset edge. Such offset edges form the required portion of the cutting trajectory. Other edges in the profile may get created when the tool is being swept along the required portion of the cutting trajectory. t_{trj} is estimated by estimating the widest portion of the profile along one of the required portions of the cutting trajectory. In order to reduce cutting forces, we want that at a given time only half portion of the tool engages in cutting. Thus, the cut-off value due to the lower bound on the trajectory length is assumed to be twice the width of the the widest portion of the profile along the required portion of the cutting trajectory. Any tool diameter bigger than this value is not expected to result in more economical machining. The procedure to compute d_{trj} involves the following steps.

- 1. Initialize $d_{trj} = 0$.
- 2. For every linear closed edge e in the profile X, do the following.
 - (a) Let l be the line that contains e.
 - (b) Use l to partition X. Let X' be the portion of the profile that lies towards the inward pointing normal vector of e. Let d be the maximum distance of any point on P' from l.
 - (c) If $d_{trj} < 2d$, then $d_{trj} = 2d$.
- 3. For every convex circular closed edge e in the profile X, do the following.

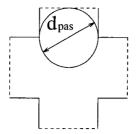


Figure 5.8: A narrow passage constraint on the tool-size for the profile shown in Figure 5.3(c).

- (a) Let p and p' be the two end points of the edge e. Let l be a semi-infinite line that is created by shooting a ray from p in the direction of edge-normal at p. Similarly, let l' be a semi-infinite line that is created by shooting a ray from p' in the direction of edge-normal at p'. Join l, e and l' to define a space curve γ.
- (b) Use γ to partition X. Let X' be the portion of the profile that lies towards the inward pointing edge-normal of e. Let d_o be the maximum distance of any point on P' from the center of e. Now, $d = d_o r_e$. Where r_e is radius of e.
- (c) If $d_{trj} < 2d$, then $d_{trj} = 2d$.

4. Return d_{trj} .

Examples. For the open pocket profile shown in Figure 5.3(c), the most stringent constraint results from a narrow passage. Figure 5.8 shows the resulting constraint on the tool size for the profile shown in Figure 5.3(c).

Figure 5.9 shows a complex open pocket profile and illustrates various upper bound on the profile. In this case, d_{pas} is most stringent constraint and d_u is equal to d_{pas} .

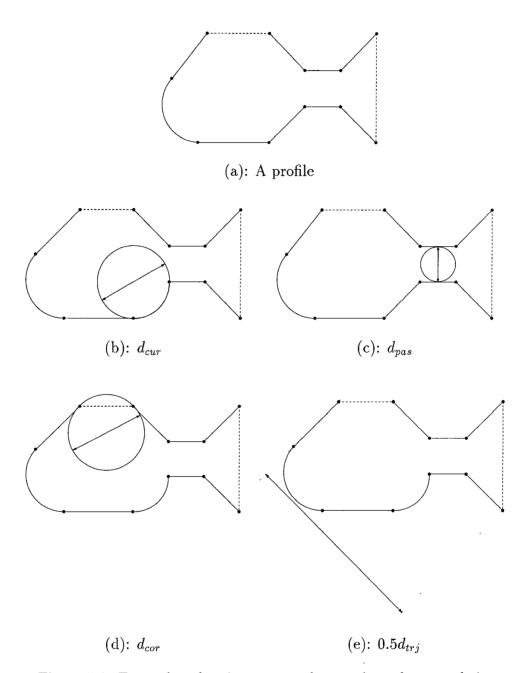


Figure 5.9: Examples of various types of upper bounds on tool size.

5.3.2.2 Facing Profiles

A face milling profile has no closed edge, therefore no geometric restrictions are imposed on the tool size. Thus, the tool size is estimated by estimating the cut-off value of tool diameter resulting from the lower bound on the cutting trajectory length. The following procedure is used to select the tool size:

1. If the profile has no linear edge, then find the minimum enclosing circle of the profile. Let the diameter of this circle be the radius of the tool.

2. Otherwise,

(a) for every linear edge e in the profile, do the following:

Find the minimum enclosing rectangle of the profile oriented along e (one of the major axis of rectangle is parallel to e). Let l be the length and w be the width of the rectangle (where, $l \geq w$).

(b) Let r be the rectangle with the minimum 2w + l among various rectangles generated in previous step. Now, let the width of r be the radius of the cuting tool.

5.3.3 Offsetting Effective Milling Profiles

After estimating the optimal tool diameter for a milling profile, the next step is to offset the milling profile to generate the cross section of the tool swept volume. The following sections describe the offsetting procedures for various types of effective milling profiles.

5.3.3.1 Closed-Pocket Profiles

A closed-pocket profile does not have any open edges, therefore the cross section of the tool swept volume is same as the pocket profile. If for a given pocket profile, the upper bound on tool size is found to be smaller than the minimum size of the available tool diameter, then the profile is considered unmachinable and will be discarded.

5.3.3.2 Open-Pocket Profiles

To offset open-pocket profiles, first the required portion of the tool swept volume is found by considering the closed edges. Next, the swept volume is generated for the open edges that could not be covered by the required portion of the swept volume. Finally, both these swept volumes are combined to generated the offset profile. The procedure for this task involves the following steps.

- 1. Let X be the given profile. Find the upper bound on tool diameter d_u for X (procedure for this task is described in Section 5.3.2.1).
- 2. If d_u is less than the minimum available tool diameter, then X is unmachinable. Discard X, and stop here.
- 3. Initialize $\mathcal{X} = \emptyset$ (\mathcal{X} will be used to store various portions of the offset profile).
- 4. For every closed edge e in X, do the following:
 - (a) Compute the offset edge e' by offsetting e by $0.5d_u$.
 - (b) Create a profile E by sweeping a circle of diameter d_u along e'.
 - (c) Add E to \mathcal{X} .

- 5. For every pair of adjoining closed edges (e_i, e_j) in X, do the following:
 - (a) If the offset edges e'_i and e'_j do not have a common end point, then create a suitable set of transition edges e_t that connect the mismatched end points. e_t is created by extending e'_i and e'_j .
 - (b) Create a transition profile E_t by sweeping a circle of diameter d_u along e_t .
 - (c) Add E_t to \mathcal{X} .
- 6. For every open edge e in X, do the following:
 - (a) If e has any adjoining closed edges, then offset the end points of e.
 - (b) Let e' be the portion of e that lies outside the profiles in \mathcal{X} . If the length of $e' \neq 0$, then do the following:
 - i. Create a profile E by sweeping a circle of diameter d_u along e'.
 - ii. If E does not intersect with part, then add E to \mathcal{X} .
 - iii. Otherwise, reset the value of d_u .

Set $d_u = d_u - 2 \times \text{maximum}$ width of intersecting area.

Go back to Step 2 and start again.

- 7. For every loop in X, form a corresponding loop of profiles in \mathcal{X} . If a loop has missing profiles (i.e., end points of edges that generated the profiles are mismatched), then add transition profiles to \mathcal{X} to complete the loop.
- 8. Compute Offset profile X_o by taking union of various profiles in \mathcal{X} and uniting it with the given profile X (i.e., $X_o = \bigcup(\mathcal{X}) \cup X$).

Figure 5.10 shows the offset profile for the profile shown in Figure 5.3(c). Figure 5.11 shows an additional example of profile offsetting.

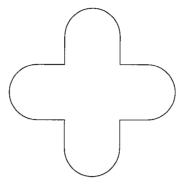


Figure 5.10: Offset profile for the profile shown in Figure 5.3(c).

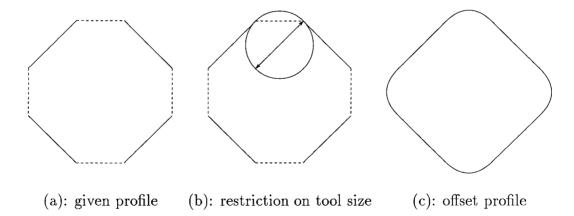


Figure 5.11: Example of profile offsetting.

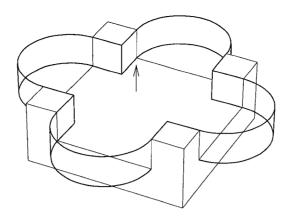


Figure 5.12: Open-pocket feature resulting from the offset profile shown in Figure 5.10.

5.3.3.3 Facing Profiles

The following procedure is used to offset a facing profile:

- If X has no linear edge, then find the minimum enclosing circle. Let d be
 the diameter of this circle. Take any two diametrically opposite points on
 d. Let l the line segment that joins these two points. Construct the offset
 profile X_o by sweeping a circle of diameter 2d along l.
- 2. Otherwise, find the tool diameter d_t and the minimum enclosing rectangle R that resulted in d_t (procedure for this task is described in Section 5.3.2.2). Let L be the line that joins the midpoints of the two parallel edges of width d_t/2 on R. Construct the offset profile by sweeping a circle of diameter d_t along L.

5.3.4 Constructing End-Milling/Face-Milling Features

After offsetting the profile, the milling features are constructed by sweeping the milling profile. The offset profile is swept to semi-infinite distance (in actual

practice, a distance larger than the maximum stock dimension) along the orientation vector of the profile. The primary feature instance is determined by truncating the swept profile with respect to the stock.

Figure 5.12 shows the open pocket feature constructed by sweeping the profile shown in Figure 5.10

5.4 Identifying Side-Milling Features

These features are used to create the slots that are not accessible from the top, but are accessible laterally. A simple side-milling feature is instantiated for a planar face u, if the following conditions are satisfied.

- 1. u is enclosed by a rectangular edge-loop.
- 2. u is not accessible semi-infinitely in the direction of its face-normal.
- 3. There are two adjoining planar surfaces v and v', such that:
 - (a) v and v' are parallel.
 - (b) u is perpendicular to v and v'.
 - (c) Let e be the common edge between u and v. Similarly, let e' be the common edge between u and v'. e and e' are concave edges.

To construct an instance of a simple side-milling feature, we need the radius of the cutting tool. The cutting tool radius is calculated as follows.

1. Find the maximum distance d of any point on v from e. Similarly, find the maximum distance d' of any point on v' from e'.

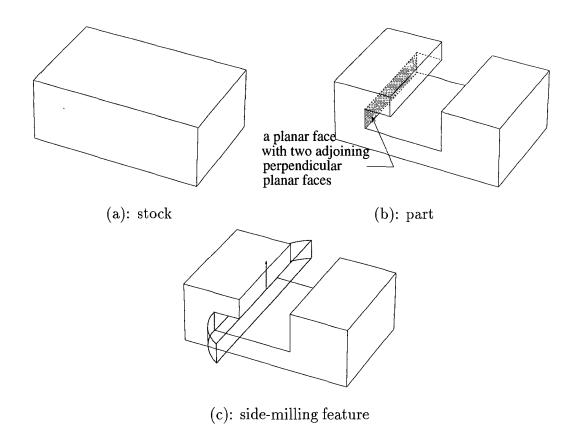


Figure 5.13: An example of identifying a simple side-milling feature.

2. Cutting tool radius $r = 2 \times \max(d, d')$.

If the accessibility or removal volume of the feature instance intersects with the part, then the feature instance is discarded. If two compatible simple sidemilling features are found, then they are combined to result in a compound side-milling feature.

Figures 5.13(a) and (b) show a stock and a part. As shown in Figure 5.13(b), the part has a planar surface that is not accessible semi-infinitely and has two adjoining perpendicular planar faces. Figure 5.13(c) shows the side-milling feature identified from this face.

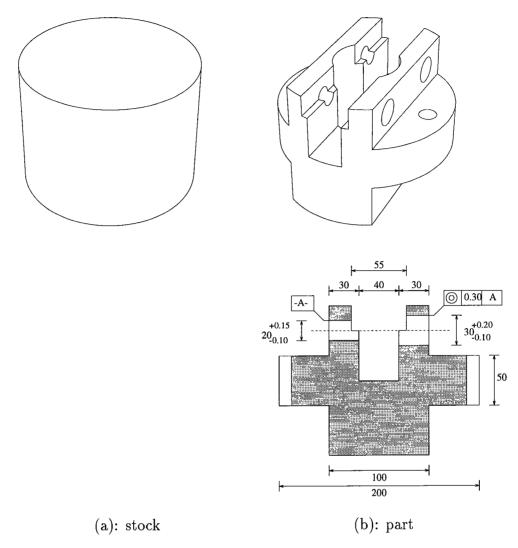


Figure 5.14: A socket.

5.5 An Example

Figure 5.14 shows the part and stock for a socket. Let us assume that this part will be machined on a 3-axis vertical machining center. The maximum available tool diameter for end-milling tools is assumed to be 50mm. Figure 5.15 shows the set of the primary end-milling features. Figure 5.16 shows the set of the primary drilling features identified. In this case, the primary feature set \mathcal{F} in

this case is given by:

$$\mathcal{F} = \{h1, h2, h3, h4, h5, h6, h7, h8, h9, h10, h11, h12, \\ s1, s2, s3, s4, s5, s6, s7, s8, s9, s10\}.$$

It should be noted that \mathcal{F} may include redundant features. For example, any machining plan will either use feature h1 or h2. Both h1 and h2 will not be used in the same plan. Moreover, some of the drilling features (such as h3) are very long and will need to be trimmed in order to result in a meaningful machining operation. During generation of machining plan, various features in \mathcal{F} will be suitably modified.

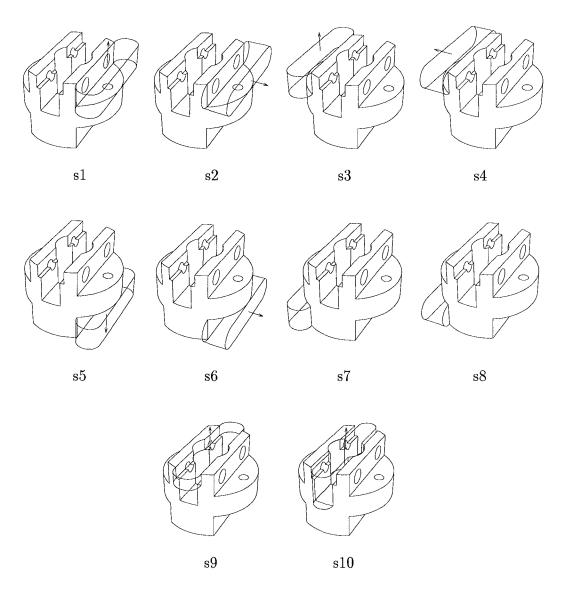


Figure 5.15: End milling features for the socket shown in Figure 5.14.

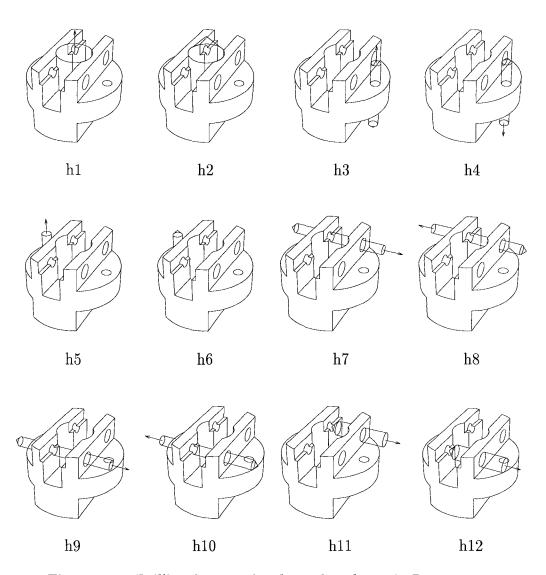


Figure 5.16: Drilling features for the socket shown in Figure 5.14.

Chapter 6

Generation of Feature-Based Models

After identifying the machining features, the next step is to generate feature-based models for the part. This step corresponds to Step 3 of the overall approach shown in Figure 1.2. Section 6.1 presents the detailed definition of feature-based models. Section 6.2 gives an overview of the FBM generation procedure developed in this thesis. Sections 6.3 and 6.4 describe various details of various steps in the FBM generation procedure.

6.1 Feature-Based Models

6.1.1 Volumetric Covers

A set of solids \mathcal{R} is a *volumetric cover* for the solid R, if it has the following properties.

- 1. Every member of \mathcal{R} is a subset of R (i.e., for every $r \in \mathcal{R}, r \subseteq R$).
- 2. Members of \mathcal{R} cover the volume of solid R (i.e., $\bigcup^*(\mathcal{R}) = R$).
- 3. No member r of \mathcal{R} is redundant (i.e., $\bigcup^* (\mathcal{R} r) \neq R$).

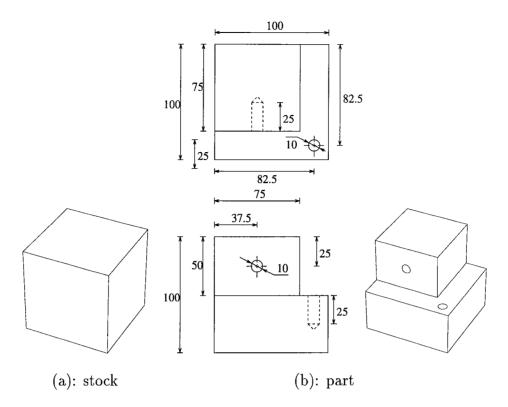


Figure 6.1: A fixture base.

6.1.2 Feature Covers

A set of features G is a feature cover for a given part P and stock S, if it has the following properties.

- 1. Sufficiency. Features in G are sufficient to describe P. If we subtract the features in G from S, we get P (i.e., $S * \bigcup_{f \in G} (\text{rem}(f)) = P$).
- 2. Necessity. No feature f in G is redundant (i.e., $S {}^* \bigcup_{g \in G \{f\}} (\operatorname{rem}(g)) \neq P$).

Note that the effective removal volumes of various features in a feature cover G form a volumetric cover of the delta volume (the volume to be machined, i.e., $\Delta = S - P$).

A feature cover corresponds to an irredundant set of machining operations that can be used to machine the part. The sufficiency condition ensures that a feature cover will have enough machining features to result in a machining plan that can remove the complete delta volume. The necessity condition implies that each feature of a feature cover will contribute to some necessary portion of the delta volume. This condition is needed to ensure that the associated machining plan will not have any redundant operation. For example, we would not generate a machining plan that removes the same portion of the delta volume twice.

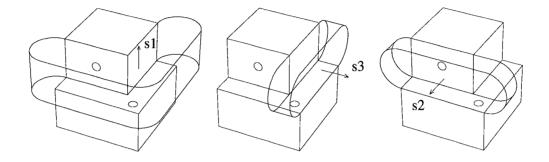
Intuitively, a feature cover is an interpretation of the delta volume as a set of machining features. Note that for a given part, there may exist many alternative feature covers. Figure 6.1 shows the part and stock for a fixture base. Figure 6.2 shows the primary feature set \mathcal{F} for this base. In this case, the maximum available tool diameter is considered 50mm. Figure 6.3 shows four different feature covers for the base shown in Figure 6.1.

Note that a set of features that forms a feature cover will not be necessarily a subset of primary features. For example, the feature cover shown in Figure 6.3(b) is not a subset of the primary feature set \mathcal{F} .

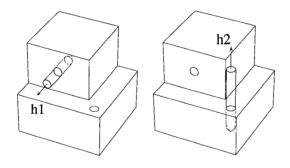
Primary Feature Covers. A feature cover G is primary if G is a subset of the primary feature set \mathcal{F} . The feature cover shown in Figure 6.3(a) is a primary feature cover.

6.1.3 Extended Feature Set

In order to examine promising machining plans, some non-primary feature covers will also need to be examined. Some of the non-primary feature covers can



(a): end-milling features



(b): drilling features

Figure 6.2: Primary feature set $\mathcal{F} = \{s1, s2, s3, h1, h2\}$ for the base shown in Figure 6.1.

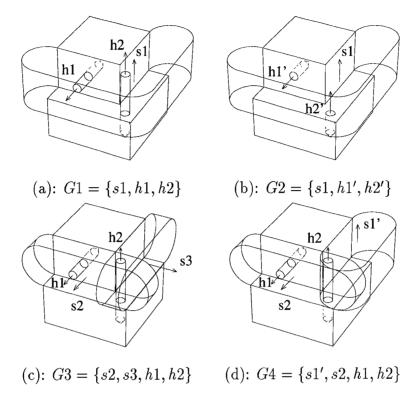


Figure 6.3: Four feature covers for the base shown in Figure 6.1.

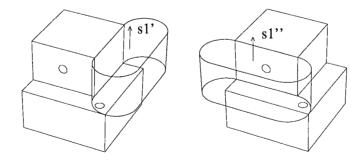


Figure 6.4: Non-primary features in the extended feature set for the base shown in Figure 6.1.

be generated by truncating the intersecting portions of the features in a primary feature cover. For example, the feature cover shown in Figure 6.3(b) can be generated by truncating the holes of the primary feature cover shown in Figure 6.3(a). However, there are feature covers of interest that cannot be generated from a primary feature cover. For example, consider two primary features f and f' such that the effective removal volume of f completely subsumes the effective removal volume of f'. In this case, there will be no primary feature cover that contains both f and f' at the same time. Now let us assume that the machining time per unit feature volume for f' is smaller than f. Let g be the feature that is generated by truncating the portion of f that intersects with f'. g corresponds to the volume of f that is not covered by f'. In this case, we would like to generate a machining plan that consists of machining operations that correspond to f' and the portion of f not covered by f'. In order to generate such a machining plan, we will be interested in a feature cover that will have f' and g. This feature cover cannot be generated by finding the feature covers over the set of primary features. In order to generate this feature cover, the primary feature set \mathcal{F} will need to be extended by including g.

To enable the generation of all promising feature covers, the primary feature set \mathcal{F} can be extended by adding zero or more non-primary features to produce an extended feature set \mathcal{F}_e . Many different types of extensions can be performed on \mathcal{F} . The following procedure describes one such possible extension of \mathcal{F} .

- 1. Initially, $\mathcal{F}_e := \mathcal{F}$.
- 2. For every feature f in \mathcal{F} , do the following.
 - (a) Let K be the set of features in \mathcal{F} such that, for every $k \in K$:

- i. the effective removal volume of k is completely subsumed by the effective removal volume of f;
- ii. k has lower machining time per unit feature volume than f. (Various procedures for estimating machining time are described in Chapter 8.)
- (b) For every non empty subset K' of K, do the following:

i.
$$W := S - * \cup (K');$$

ii. let g be the truncation of f with respect to W;

iii. add g to \mathcal{F}_e .

3. Return \mathcal{F}_e .

Consider the base shown in Figure 6.1, the primary feature set for this part (shown in Figure 6.2) contains an end milling feature s1 that completely subsumes s2 and s3. s2 and s3 have half the depth of s1 and thus involve lower number of machining passes. Thus, the machining time per unit feature volume is lower for s2 and s3 in comparison with s1. Machining time for a feature is estimated by mapping the feature to its corresponding machining operation (details of the procedure for estimating machining time are described in Chapter 8). In this case, two non-primary features s1' and s1'' (shown in Figure 6.4) are added to the primary feature set. In this case, the extended feature set is

$$\mathcal{F}_e = \{s1, s1', s1'', s2, s3, h1, h2\}.$$

If there are no features in the primary feature set \mathcal{F} that subsume any other features with lower machining time per unit feature volume, then the extended feature set is the same as the primary feature set. For example, in case of the

socket shown in Figure 5.14, the set of primary features (shown in Figures 5.15 and 5.16) does not have any feature that completely subsumes any other feature. Therefore in this case, the extended feature set is the same as the primary feature set.

6.1.4 Definition of a Feature Based Model

A set of features F is a feature-based model (FBM) for P, S, and \mathcal{F}_e , if it has the following properties:

- 1. F forms a feature cover on P and S;
- 2. F is a subset of \mathcal{F}_e .

Intuitively, an FBM is an interpretation of the delta volume in terms of features from the extended feature set. A part may have more than one FBM. For example, the feature covers shown in Figure 6.3(a), (c) and (d) are also FBMs.

6.2 Overview of FBM Generation Procedure

An FBM corresponds to a set of machining operations that are sufficient to create the part from the stock. Various machining plans can be generated from FBMs by suitably truncating the features and identifying the precedence constraints.

In general for a given part, there can be a very large number of FBMs. We will not be interested in generating FBMs that result in unpromising machining plans. A machining plan will be considered unpromising if it violates any design or machining constraints or results in excessive machining cost. A

variety of heuristic techniques are used to control the generation of FBMs. Sections 6.4.2, 6.4.1, and 6.4.3 describe various pruning techniques for discarding FBMs that result in unpromising plans (i.e. plans with very high production time).

Given P, S and the primary feature set \mathcal{F} , first the extended feature set \mathcal{F}_e is built by incorporating non-primary features. The method for this task is described in Section 6.1.3. Various FBMs are generated by finding the feature covers over \mathcal{F}_e . The FBM generation procedure involves the following two steps.

- 1. Generating volumetric covers of effective removal volumes. The set of effective removal volumes is found from various features in the extended feature set. Note that more than one feature can have the same effective removal volume. Then various sets of effective removal volumes forming volumetric covers of the delta volume are found. Let \mathcal{C} be the set of various volumetric covers of the delta volume. Section 6.3 describes details of the procedure for this step.
- 2. Generating FBMs from the volumetric covers. For every cover found in the previous step, FBMs are generated by replacing the effective removal volumes by corresponding features. Note that since more than one feature can have the same effective removal volumes. A volumetric cover may result in more than one FBM. As and when any FBM is generated, the corresponding machining plans are also generated and evaluated. Any FBM that is not expected to result in a better plan will not be generated and evaluated. Section 6.4 describes the procedure for this task and explains various pruning heuristics that are used to discard unpromising FBMs.

6.3 Generating Volumetric Covers of Effective Removal Volumes

Two procedures are used to generate various volumetric covers. The first procedure Initialize-Covers assigns initial values to some variables, and calls Generate-Covers to generate the covers.

INITIALIZE-COVERS involves three steps. In the first step, this procedure computes the set \mathcal{R} of effective volumes of various features in the extended feature set \mathcal{F}_e . In the second step, this procedure splits \mathcal{R} into two parts. One part, \mathcal{I} , contains each volume that is not subsumed by the other volumes in \mathcal{R} . These volumes are guaranteed to be in every volumetric cover for \mathcal{R} . The other part, $\mathcal{R} - \mathcal{I}$, contains each volume that is subsumed by the other volumes in \mathcal{R} . These volumes may appear in some volumetric covers for \mathcal{R} , but will not appear in all of them. In the third step, this procedure calls a recursive procedure GENERATE-COVERS to compute the volumetric covers. INITIALIZE-COVERS is described below.

procedure Initialize-Covers (\mathcal{F}_e)

- 1. For the features in \mathcal{F}_e , let \mathcal{R} be the set of effective removal volumes with respect to S (i.e., $\mathcal{R} = \{\text{eff}(f, S) : f \in \mathcal{F}_e\}$).
- 2. Let \mathcal{I} contain every volume $r \in \mathcal{R}$ that is not subsumed by the other volumes in \mathcal{R} (i.e., $\mathcal{I} = \{r : r -^* \bigcup_{q \in \mathcal{R} \{r\}} (q) \neq \emptyset\}$). Note that each volume $r \in \mathcal{I}$ is guaranteed to be in every irredundant cover for \mathcal{R} .
- 3. $C = GENERATE-COVERS(\mathcal{R} \mathcal{I}, \mathcal{I}).$

GENERATE-COVERS is a backtracking algorithm that looks for sets of effective removal volumes that form volumetric covers for the delta volume. Each such volumetric cover corresponds to one or more FBMs. Thus, for each set cover that GENERATE-COVERS finds, in Section 6.4, we will generate one or more FBMs F such that the effective removal volumes of the features in F are identical to the volumes in Y.

GENERATE-COVERS takes two arguments, X and Y. Y is the partial set cover that has been built up already, and X is a set of volumes that can potentially be added to Y to complete the set cover. GENERATE-COVERS calls itself recursively to remove elements from X and add them to Y. Upon entry, if Y contains a complete cover, Y is stored in C.

In cases where X is nonempty, the efficiency of GENERATE-COVERS depends on the order in which it chooses the volumes in X. To make the procedure efficient, in Step 4(a) our heuristic is to choose the volume r in X which covers the maximum portion of the uncovered delta volume. This corresponds to choosing a $r \in X$ such that $r \cap^* (\Delta - ^* \cup (R))$ is maximized. GENERATE-COVERS is described below.

procedure GENERATE-COVERS(X, Y)

- 1. If Y contains a volume r that is subsumed by the other volumes in Y (i.e., $\cup^*(Y \{r\}) = \cup^*(Y)$), then return \emptyset , because Y is redundant.
- 2. Otherwise, if the delta volume is completely covered by Y (i.e., $\Delta \subseteq \cup^*(Y)$), then return $\{Y\}$, because we have found an irredundant cover.
- 3. Otherwise, if the volumes in Y and X cannot cover the delta volume (i.e., $\Delta \supset \cup^*(Y \cup X)$), then return \emptyset , because Y is not feasible.

- 4. Otherwise, do the following:
 - (a) Choose a volume r in X (see discussion above).
 - (b) Return GENERATE-COVERS $(X \{r\}, Y \cup \{r\}) \cup$ GENERATE-COVERS $(X \{r\}, Y)$.

Example 1. Consider the socket shown in Figure 5.14. In this case, the set extended set \mathcal{F}_e is the same as the primary feature set shown in Figures 5.15 and 5.16. In this case,

$$\mathcal{R} = \{r1, r2, r3, r4, r6, r7, r8, r9, r10, r11, r12, r13\},\$$

where

$$r1 = \text{eff}(s1, S) = \text{eff}(s2, S),$$
 $r2 = \text{eff}(s3, S) = \text{eff}(s4, S),$
 $r3 = \text{eff}(s5, S) = \text{eff}(s6, S),$ $r4 = \text{eff}(s7, S) = \text{eff}(s8, S),$
 $r5 = \text{eff}(s9, S),$ $r6 = \text{eff}(s10, S),$
 $r7 = \text{eff}(h1, S) = \text{eff}(h2, S),$ $r8 = \text{eff}(h3, S) = \text{eff}(h4, S),$
 $r9 = \text{eff}(h5, S) = \text{eff}(h6, S),$ $r10 = \text{eff}(h7, S) = \text{eff}(h8, S),$
 $r11 = \text{eff}(h9, S) = \text{eff}(h10, S),$ $r12 = \text{eff}(h11, S),$
 $r13 = \text{eff}(h12, S).$

In this case, every volume in set \mathcal{R} is irredundant. Therefore, $\mathcal{I} = \mathcal{R}$. Initialize-Covers calls Generate-Covers with

$$X = \emptyset$$

and

$$Y = \{r1, r2, r3, r4, r5, r6, r7, r8, r9, r10, r11, r12, r13\}.$$

In this case, Y is already a volumetric cover. Therefore, in the second step of Generate-Covers Y is saved in \mathcal{C} as a volumetric cover. In fact in this case, only one volumetric cover is found. This cover is:

$$\{r1, r2, r3, r4, r5, r6, r7, r8, r9, r10, r11, r12, r13\}.$$

Example 2. Consider the base shown in Figure 6.1. In this case, the set of extended feature is given by the features shown in Figures 6.2 and 6.4. In this case,

$$\mathcal{R} = \{r1, r2, r3, r4, r5, r6, r7\},\$$

where

$$r1 = \text{eff}(h1, S),$$
 $r2 = \text{eff}(h2, S),$
 $r3 = \text{eff}(s1, S),$ $r4 = \text{eff}(s1', S),$
 $r5 = \text{eff}(s1'', S),$ $r6 = \text{eff}(s2, S),$
 $r7 = \text{eff}(s3, S).$

In this case, only r1 and r2 are irredundant. Therefore, $\mathcal{I} = \{r1, r2\}$.

INITIALIZE-COVERS calls GENERATE-COVERS with

$$X = \{r3, r4, r5, r6, r7\}$$

and

$$Y = \{r1, r2\}.$$

In this case, Y is neither redundant nor a cover. Therefore, GENERATE-COVERS proceeds with Step 4 and generates the following four covers:

$$\{\{r1,r2,r3\},\{r1,r2,r6,r7\},\{r1,r2,r4,r6\},\{r1,r2,r3,r7\}\}$$

6.4 Generating FBMs from Volumetric Covers

Two main procedures are used to generate various FBMs. The first procedure Initialize-FBM-Generation takes the set of volumetric covers \mathcal{C} generated by Generate-Covers and for each volumetric cover \mathcal{R} in \mathcal{C} , calls a recursive procedure Cover-To-FBMs to generate various FBMs. Efficiency of Initialize-FBM-Generation depends on the order in which various covers in \mathcal{C} are examined. Our heuristic is to examine various covers in the increasing order of the lower bound on the estimated production time on any machining plan resulting from the cover. Initialize-FBM-Generation is described below.

procedure Initialize-FBM-Generation(C)

For every \mathcal{R} in \mathcal{C} , call COVER-TO-FBMs(\mathcal{R}, \emptyset).

Each time that GENERATE-COVERS finds an irredundant cover for the delta volume, the next step is to generate one or more primary FBMs from this cover. This is done by using the depth-first branch-and-bound algorithm COVER-TO-FBM. COVER-TO-FBMS takes two arguments, \mathcal{R} and \mathcal{G} . \mathcal{G} is the partial FBM that has been built up already, and \mathcal{R} is the set of volumes from which features need to be generated in order to complete \mathcal{G} . COVER-TO-FBMs calls itself recursively to remove volumes from \mathcal{R} , and try alternative completions of \mathcal{G} consisting of alternative features corresponding to these volumes. For each FBM that COVER-TO-FBM generates, it calls the algorithm GENERATE-PLANS (see Chapter 7 for details), in order to generate one or more machining plans and evaluate their plan rating.

procedure COVER-TO-FBMs(\mathcal{R}, G)

- 1. If $h(G, \mathcal{R})$ is greater than the plan rating of the best machining plan seen so far, then return, because G is unpromising (the pruning heuristic $h(G, \mathcal{R})$, described in Section 6.4.1, returns the lower bound on the plan rating for any machining plan resulting from features in the set G)
- 2. Otherwise, if R = ∅, then call GENERATE-PLANS(G) and return, because we have found a promising FBM. GENERATE-PLANS, described in Chapter 7, generates various machining plans resulting from G. Whenever GENERATE-PLANS generates a plan, it also evaluates it to see if it is better than the previously generated best machining plan.
- 3. Otherwise, do the following:
 - (a) Choose an effective removal volume r in \mathcal{R} .
 - (b) Since more than one feature in \mathcal{F} can have r as its effective removal volume, let F_r be the set of all such features (i.e., $F_r = \{f : \text{eff}(f, S) = r\}$).
 - (c) For each feature $g \in F_r$, do the following:
 - i. If g is asymmetric to any features in G, then discard g (conditions that result in feature asymmetry are described in Section 6.4.2).
 - ii. Otherwise, if g has tolerance incompatibility with any features in G, then discard g (conditions that lead to tolerance incompatibility are defined in Section 6.4.3).
 - iii. Otherwise, call Cover-To-FBMs($\mathcal{R} \{r\}, G \cup \{g\}$).

The above procedure performs three types of pruning to discard unpromising FBMs. In Step 1 of the above procedure, every partial or complete FBM that is not expected to result in a better machining plan than the current best plan is pruned. This is accomplished by using heuristic function $h(G, \mathcal{R})$ that returns the lower bound on the plan rating resulting from features in G (see Section 6.4.1 for details). Step 3(c)i allows us to prune the FBMs involving asymmetric features (see Section 6.4.2 for details). Typically, FBMs with asymmetric features result in machining plans with poorer rating compared to the plans generated from the FBMs with symmetric features. Step 3(c)ii allows us to prune the FBMs that cannot result in a machining plan capable of meeting the design tolerances (see Section 6.4.3 for details). In absence of any pruning, for the socket shown in Figure 5.14, there exist 512 FBMs. With the pruning steps, above procedure only generates 8 FBMs.

If promising FBMs have been generated and examined first, then we need not examine any FBM that is not expected to result in a better machining plan. Thus, the computational efficiency (but not the correctness) of COVER-TO-FBMs depends on which effective removal volume is chosen (Step 3(a) of COVER-TO-FBMs). Our heuristic is to choose the one that has minimum number of features associated with it, i.e., to choose $r \in \mathcal{R}$ that minimizes the cardinality of the set $\{f : \text{eff}(f, S) = r\}$). The efficiency of COVER-TO-FBMs also depends on the order in which it examines the features in F_r (Step 3(c) of COVER-TO-FBMs). Our heuristic is to examine features $g \in F_r$ in order of increasing value of the pruning heuristic $h(G \cup \{g\}, \mathcal{R} - \{r\})$.

6.4.1 Plan Rating Based Pruning

The heuristic function $h(G, \mathcal{R})$ gives the lower bound on the plan rating for any machining plan resulting from the features in G, i.e., no plan resulting from G will have better rating than $h(G, \mathcal{R})$. In this thesis, the plan rating for a given machining plan is based on the estimated production time (see Chapter 8 for details). Therefore, $h(G, \mathcal{R})$ gives the lower bound on the production time.

Each time that COVER-TO-FBMs is called, \mathcal{R} is a set of effective removal volumes, and G is a set of features such that $\mathcal{R} \cup \{\text{eff}(g,S) : g \in G\}$ is a volumetric cover for the delta volume. For all sets \mathcal{R} and G that satisfy this property, we define

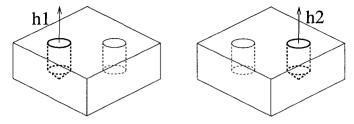
$$h(G,\mathcal{R}) = L_s(G) \times T_s + (1+\beta) \sum_{g \in G} L_{mt}(g),$$

where

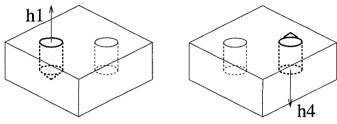
- $L_s(G)$ is a lower bound on the number of setups needed to machine G. For three-axis machining centers, $L_s(G)$ is the cardinality of the set $\{\vec{v}(g):g\in G\}$, where $\vec{v}(g)$ is the orientation vector for feature g.
- T_s is the average setup time (see Chapter 8 for details).
- L_{mt}(g) is a lower bound on the time required to machine feature g. This
 is the time required to machine the irredundant portion of the effective
 removal volume of g. Let solid g_I = eff(g, S)-*∪(R)-*∪_{f∈G-{f}}(eff(f, S)).
 Now L_{mt}(g) is computed as

 $L_{mt}(g) = \text{machining time for } g \times (\text{volume of } g_I/\text{volume of eff}(g, S)).$

(See Chapter 8 for details of various procedures for the estimation of machining time.)



h1 and h2 are symmetric



h1 and h4 are asymmetric

Figure 6.5: Examples of symmetric and asymmetric features.

• β is the fraction of machining time that accounts for the auxiliary time (see Chapter 8 for details).

Heuristic $h(G, \mathcal{R})$ is very useful in discarding FBMs that involve features from many different approach directions. Consider the base shown in Figure 6.1, the set $\{h1, h2, s2, s3\}$ (shown in Figure 6.2) is an FBM for this part. This FBM requires a minimum of three approach directions. $h(G, \mathcal{R})$ allows discarding this FBM in favor of other FBMs that require only two approach directions.

6.4.2 Feature Symmetry Based Pruning

A feature g is considered symmetric to a feature f, if f and g satisfy the following conditions.

1. f and g are of the same type (i.e., op(f) = op(g)).

- 2. f and g have the same parameters (i.e., param(f) = param(g)).
- 3. f and g have the same orientation vectors (i.e., $\vec{v}(f) = \vec{v}(g)$)
- 4. Let π be the plane defined by the datum point and orientation vector of f. The datum point of g lies on π .
- 5. Faces created by f and g have been assigned identical tolerances.

For example, the features h1 and h2 shown in Figure 6.5 are symmetric to each other.

A feature g is considered asymmetric to a feature f, if f and g satisfy the following conditions.

- 1. Let r be the effective removal volume of g (i.e, r = eff(g, S)). There exists a feature g' in \mathcal{F}_e that has r as its effective removal volume (i.e, r = eff(g', S)).
- 2. f and g' are symmetric.
- 3. The estimated machining time for g is greater than or equal to the estimated machining time for g'.

For example, the features h1 and h4 shown in Figure 6.5 are asymmetric to each other.

Any FBM involving asymmetric features requires that two very similar portions of the delta volume to be machined by two operations that are either of different types, or are performed in different setups. Such FBMs are considered unpromising as they result in plans with lower plan ratings compared to the plans that are generated from the FBMs with symmetric features. For the

socket shown in Figure 5.14, no FBM is generated that involves both feature s1 and s4 at the same time.

6.4.3 Tolerance Incompatibility Based Pruning

In general, machining accuracy is higher if two faces are machined in the same setup. Thus, if two faces in the part have tight tolerance between them, then these two faces need to be machined in the same setup. An FBM will be considered unpromising, if it only results in machining plans that create the faces associated with tight tolerances in different setups.

Let u and u' be the two part faces that involve tight tolerance (i.e., tolerance value is smaller than error due to setup change). If u and u' are machined in different setups, the error introduced by setup change will result in poor machining accuracy. Thus, the tolerance between u and u' will not be achieved. Let f be a feature that creates u, let f' be a feature that creates u'. f and f' will have tolerance incompatibility if f and f' have different orientation vectors.

Any FBM involving features with tolerance incompatibility is considered unpromising. Two pairs of holes in Figure 5.14 have tight concentricity tolerance. Features h8 and h11 (shown in Figure 5.16) create a pair of faces with tight tolerances and have different orientation vectors. Therefore, h8 and h11 have tolerance incompatibility with respect to each other. For the socket shown in Figure 5.14, no FBM will be generated that will have both h8 and h11 at the same time.

Chapter 7

Generation of Machining Plans

After generating feature-based models, the next step is to generate machining plans from feature-based models. This step corresponds to Step 4(a) of the overall approach shown in Figure 1.2. Section 7.1 presents an overview of machining plan generation. Section 7.2 describes various machining considerations that lead to precedence constraints among machining operations. Section 7.3 presents the procedure developed in this thesis for generating machining plans from a feature based model. Section 7.4 presents various pruning heuristics developed in this thesis for discarding unpromising machining plans.

7.1 Overview of Machining Plan Generation

Due to a variety of machining considerations such as accessibility, approachability, datum dependency, and so forth, the features in an FBM cannot be machined in any arbitrary order. Instead, these considerations introduce precedence constraints requiring that some features be machined before or after other features. For the purpose of this thesis, a machining plan considered to be a set of machining operations with precedence constraints.

Generation of machining plans from an FBM involves the following steps. First, various features in a given FBM are examined to find the set of precedence constraints. Next, depending upon the set of precedence constraints, the shared portions of various features are truncated such that the truncated features form a feature cover. A feature cover along with a set of precedence constraints is called an *ordered feature cover* (a detailed definition is given in Section 7.2.3). Finally, ordered feature covers are mapped into machining plans.

In order to correctly estimate machining accuracy and plan rating, it is very important to assign correct precedence constraints among intersecting features. The shared volume between the two intersecting features is removed during machining of the feature being machined first. Therefore, the feature being machined later may have different effective removal volume at the time of machining. Such changes in effective removal volumes affect the machining accuracy and plan rating. In many cases, a pair-wise examination of intersecting features is sufficient to determine the preferable machining order of the two intersecting features. However, in some cases, such examination is not adequate and both the alternative possibilities need to be examined. In such cases, an FBM may result in more than one machining plan.

7.2 Precedence Constraints in Machining

Precedence constraints result from a wide variety of machining considerations. Some of the machining considerations lead to strict precedence constraints among the features. These types of precedence constraints cannot be violated during machining. The machining considerations leading to strict precedence con-

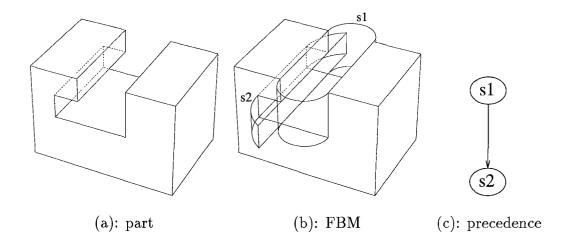


Figure 7.1: An example of an accessibility precedence constraint. s2 is not accessible until s1 has been machined.

straints are described in Section 7.2.1. Some other types of precedence constraints result from preferred machining practices, and in most situations adhering to these precedence constraints result in efficient machining plans. Various precedence preference heuristics are described in Section 7.2.2. However, the precedence constraints resulting from these heuristics are not strict in nature and depending upon the requirements of the overall machining plan, these constraints can be omitted.

7.2.1 Strict Precedence Constraints

Let F be an FBM, and let f and g be any two features in F. The following types of machining considerations result in strict precedence constraints among f and g.

1. Accessibility. If the accessibility volume of f intersects with the effective removal volume of g (i.e., $acc(f) \cap^* eff(g, S) \neq \emptyset$), then this means that

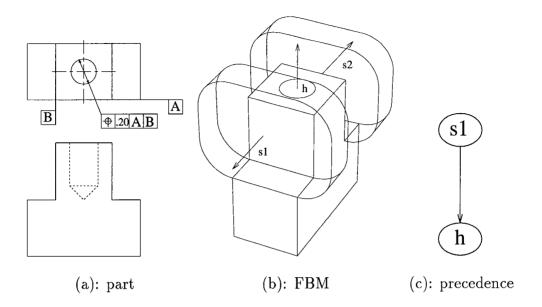


Figure 7.2: An example of a datum-dependency precedence constraint. Because the features have different orientations, in this cover they cannot be done in the same setup on a three-axis vertical machining center. Thus, because of the tolerance specification, s1 must be machined before h.

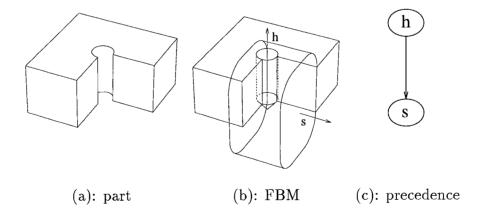


Figure 7.3: An example of approachability precedence constraint. If s were machined before h, then h's required entry face would not be present.

the cutting tool approaches f through the volume occupied by g, and thus g must be machined before f. An example of this type of precedence constraint is shown in Figure 7.1, in which the side slot s2 must be machined after the top slot s1. These types of precedence constraints can be identified by pair-wise examination of the features. The removal volumes of the features involving this type of precedence constraint either are adjacent to each other or intersect with each other.

- 2. **Datum-dependency.** If f and g have different approach directions and f creates the datum surface for the position tolerance of g, then f must be machined before g. These types of precedence constraints can be determined by pair-wise examination of the features. An example of this type of precedence constraint is shown in Figure 7.2, in which s1 must be machined before h.
- 3. Approachability. If g is machined before f, then f will not be approachable (i.e., the approach conditions for f will be violated). An example of this type of precedence constraint is shown in Figure 7.3, in which hole h must be machined before slot s. If s is machined before h, the boundary of the entry face of h will not be a complete circle. Since the approach condition for a feature is defined with respect to the workpiece, it is not always possible to find this type of precedence constraint by pair-wise examination of features.

Sometimes, for a given FBM, various strict precedence constraints may be in conflict with each other. Such conflicts lead to cyclic constraints. FBMs involving conflicting constraints do not result in valid machining plans, and are

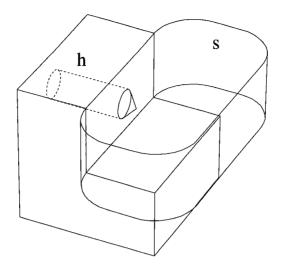


Figure 7.4: An example of insignificant feature intersection. Since h intersects s only at h's conical bottom, this will not introduce any precedence requirements between s and h.

discarded. In some cases, additional feature(s) could be added to an FBM. These additional features would enable the approachability of an already existing feature in the FBM, and would help in generating valid machining plans from otherwise unpromising FBMs. However, in this thesis, such cases are not handled, and no additional features are added to any FBM.

7.2.2 Precedence Preference Heuristics

Quite often precedence preference heuristics can be used to determine the preferred precedence constraints between the two intersecting features. Such preference heuristics are based on recommended machining heuristics that are expected to result in efficient machining plans.

In order to apply a precedence preference heuristic, the pair of intersecting

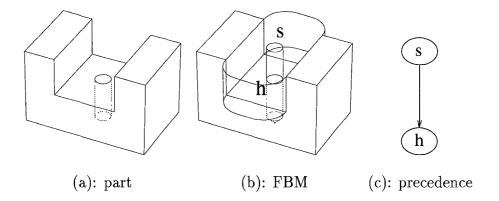


Figure 7.5: An example of a precedence constraint introduced by the open-pocket end-milling/drilling precedence heuristic. In this case, machining s before h will reduce the machining time.

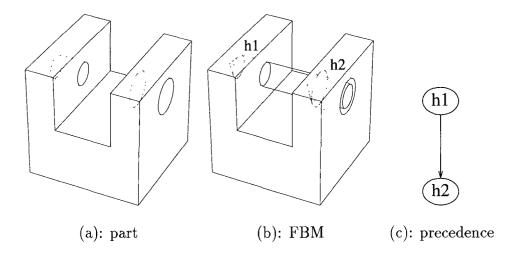


Figure 7.6: An example of a precedence constraint introduced by the drilling/drilling precedence heuristic.

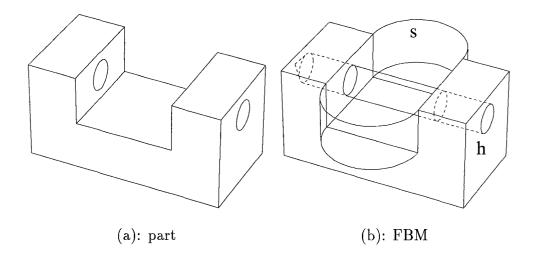


Figure 7.7: An example of an undecidable precedence constraint.

features should have significant intersection. Two features will not have a significant intersection if the order in which the features are machined does not affect the machining accuracy and plan rating. In many cases, based on the intersection volume and features involved, the intersection between the two features can be classified as insignificant. For example, intersection of the conical bottom of a drilling feature with any other feature is considered insignificant intersection. An example of insignificant feature intersection is shown in Figure 7.4. In this case, only conical bottom of h intersects with s.

Based on the spatial location of the intersection volume with respect to the intersecting features, a number of precedence preference heuristics can be formulated. These heuristics determine the preferred order of machining the two features. In this thesis, precedence preference heuristics will only be used to assign precedence constraints between features having the same approach direction. Since most of the precedence preference heuristics are based on local geometric information, assigning preferred precedence constraints between fea-

tures having different approach directions may lead to non-optimal machining plans that require extra setups. The following are two examples of precedence preference heuristics.

- 1. Open-Pocket End-Milling/Drilling Precedence Heuristics: If an open-pocket end-milling feature completely contains the cross-section of the drilling feature inside its profile, then the open-pocket end-milling feature should be machined before the drilling feature. An example of this heuristic is shown in Figure 7.5. In this case, it is preferable to machine s before h.
- 2. Drilling/Drilling Precedence Heuristics: If two concentric drilling feature having same approach direction and intersect, then the hole with smaller diameter should be machined first. An example of this heuristic is shown in Figure 7.6. In this case, it is preferable to machine h1 before h2.

Similar heuristics can be defined for different pairs of machining features. However, in many cases, additional qualifying conditions are needed. These conditions determine the applicability of the heuristic in case of the feature intersections that involve more than two features at the same time.

In many situations, pair-wise examination of two intersecting features will not be sufficient to determine the precedence constraint among them. For example, in case of the drilling and end milling features shown in Figure 7.7, there is no precedence preference heuristic to assign the precedence constraint among these two features. In such cases, both the possibilities are examined, and the machining plan is selected based on the estimated machining accuracy and plan rating.

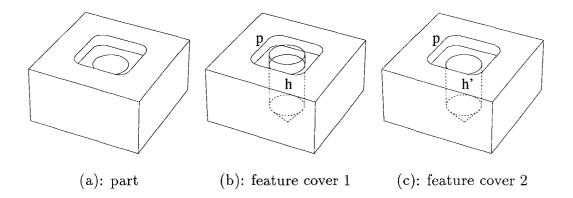


Figure 7.8: Feature covers for illustration of feature minimality precedence constraint.

7.2.3 Ordered Feature Covers

As described in Section 7.1, after assigning the precedence constraints, various features are truncated to eliminate the duplication of shared volume. The feature truncation is performed in such a way that the truncated features form a feature cover.

In order to perform the evaluation of machining accuracy and plan rating on the partially ordered machining features, feature minimality precedence constraints are needed. These constraints do not result from any machining consideration, but are needed to generate consistent ordered feature covers. Feature minimality constraints are defined as follows. Let us assume that f and f' are two features in a feature cover. Suppose that machining f' before f would allow us to machine rem(f) using a smaller feature g of the same class as f. In such cases, if we want to consider the possibility of machining f' before g, then we will use a feature minimality constraint to constrain f to be machined before f' (otherwise, we might be machining g rather than f which would involve different machining accuracy and rating). An example is shown in Figure 7.8. If

we want to generate the ordered feature cover from the feature cover shown in Figure 7.8(b), then we will have to constrain the hole h to be machined before the pocket p. If we do not have a feature minimality precedence constraint in this case, there will be the possibility of machining h after p. If we machine h after p, we will be actually machining a smaller hole h'. This will actually correspond to a different feature cover (shown in Figure 7.8(c)). The estimation of machining accuracy and rating for h and h' will be different. Thus in order to correctly estimate machining accuracy and plan rating, feature minimality precedence constraints are used. Note that in the above example, both feature covers will be used to generate plans.

An ordered feature cover (G, C) consists of a feature cover G along with the following set of precedence constraints C:

- Feature minimality. C contains a constraint f → f' for every pair of features f, f' such that machining f' before f would allow us to machine the volume machined by f using a smaller feature.
- 2. Accessibility. C contains a constraint $f \to f'$ for every pair of features f, f' such that f' will not be accessible until we machine f.
- 3. Approachability. C contains a constraint $f \to f'$ for every pair of features f, f' such that f' will not be approachable until we machine f.
- 4. **Datum Dependency.** C contains a constraint $f \to f'$ for every pair of features f, f' such that machining f creates the datum surface for f'.

It should be noted that after truncating various features, the precedence constraints resulting from various precedence preference heuristics (described in Section 7.2.2) are represented as precedence constraints of either the feature minimality type, the accessibility type, the approachability type, or the datum dependency type.

7.2.4 Machining Plans

A machining plan (O, C) is a set of machining operations O (along with the recommended cutting parameters) and a set of precedence constraints C such that:

- 1. The set of features G corresponding to the various machining operations in O forms a feature cover.
- 2. (G,C) is an ordered feature cover.

Figure 7.9 shows a machining plan for the base shown in Figure 6.1. An arrow between two operations indicates a precedence constraint. The cutting parameters for various machining operations are based on the recommendations of the Machinability Data Center's handbook [53]. An attempt is made to select the cutting parameters that enable the highest possible metal removal rate.

7.3 Procedure for Generating Machining Plans

After generating FBMs, the next step is to generate the associated machining operations along with the precedence constraints. The procedure for generation of machining plans works as follows. First, ordered feature covers are generated by finding precedence constraints on a given FBM, and truncating the intersecting portions of various features in the FBM. There might be alternative sets

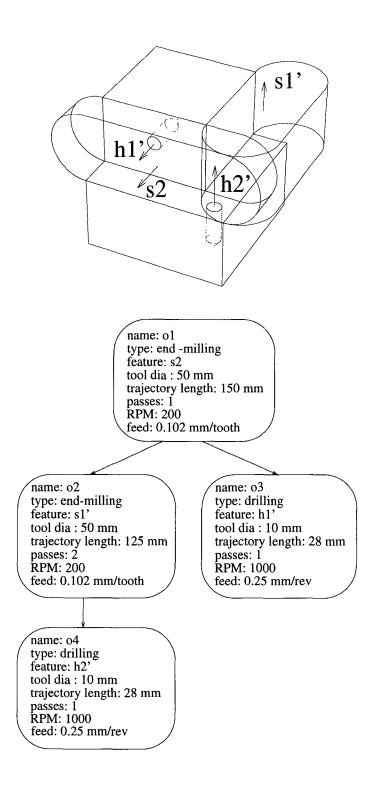


Figure 7.9: A machining plan for the base shown in Figure 6.1

of precedence constraints for a given FBM, resulting in more than one ordered feature cover. If any ordered feature cover results in violation of any common machining practice, then that ordered feature cover is discarded. The next step is to generate the machining plan from an ordered feature cover. This involves mapping each feature of the ordered feature cover to the machining operation capable of creating the feature, and applying the precedence constraints to the machining operations. Every machining plan that is capable of meeting the design tolerance specifications is evaluated and its rating is computed. If this machining plan is worse than the current-best machining plan, then the current plan is discarded. Otherwise, the current best machining plan is updated. Detailed steps of the procedure for generation of machining plan GENERATE-PLANS are described below.

procedure GENERATE-PLANS(F)

- 1. Call TRIM-FBM(F). This procedure trims the unuseful portions of the feature in FBM F. Details of this procedure are described in Section 7.3.1.
- 2. Let $\mathcal{I} = \{(f_1, f'_1), (f_2, f'_2), \dots, (f_n, f'_n)\}$ be all pairs of features in F that have significant intersections.
- 3. For every (f_i, f'_i) in \mathcal{I} , do the following:
 - (a) If there exists a precedence preference heuristic that orders (f_i, f'_i) , then add the resulting precedence constraint to C_P , and remove (f_i, f'_i) from \mathcal{I} .
 - (b) Otherwise, if (f_i, f'_i) involve any approachability precedence constraint, then add the resulting precedence constraint to C_P , and remove (f_i, f'_i) from \mathcal{I} .

- (c) Otherwise, if (f_i, f'_i) involve any accessibility precedence constraint, then add the resulting precedence constraint to C_P , and remove (f_i, f'_i) from \mathcal{I} .
- 4. For every consistent set C_I of precedence constraints on the pairs of intersecting features in $\mathcal{I} = \{(f_1, f'_1), (f_2, f'_2), \dots, (f_n, f'_n)\}$, i.e., every consistent set C_I of precedence constraints such that for each i, C_I contains either the constraint $f_i \to f'_i$ or the constraint $f'_i \to f_i$ but not both, do the following:
 - (a) Let C be the set of precedence constraints that is formed by combining C_P and C_I (i.e., $C = C_P \cup C_I$).
 - (b) Let f_1, f_2, \ldots, f_n be any total ordering of F that is consistent with C. Such a total ordering can be generated using topological sorting [14]. This total ordering is not unique, but since C totally orders intersecting features, it can be shown that we will get exactly the same machining plan regardless of which total ordering is produced by the topological sorting algorithm.
 - (c) For every i > 0, let g_i be the truncation of f_i with respect to the workpiece W_i = S -* (f₁ ∪* ... ∪* f_{i-1}). Truncation returns the smallest feature g of f's type and orientation such that g can remove the volume removed by f from W_i, i.e., eff(g, W_i) = eff(f, W_i). (See Chapter 3, for details and examples.) If f_i violates any dimensional constraints, or is not accessible/approachable in W_i after truncation, then discard C and skip Step (d). Section 7.4.1 describes the details and examples of this type of pruning.
 - (d) Let $G = \{g_1, \ldots, g_n\}$. Add the ordered feature cover (G, C) to the set

 \mathcal{G} of all ordered feature covers found so far. (Note that since the precedence constraints were assigned only on intersecting features, these ordered feature covers don't have datum dependency type precedence constraints. These types of precedence constraints are incorporated in Step 6(a).)

- 5. Call Relax-Prec-Const(\mathcal{G}). This procedure, described in Section 7.3.2, detects situations in which some of the precedence constraints can be eliminated.
- 6. For every ordered feature cover $(G, C) \in \mathcal{G}$, do:
 - (a) Augment C by incorporating the datum-dependency type of precedence constraints on features in G.
 - (b) If G poses fixturability problems, then discard (G, C). Section 7.4.2 describes the details of this type of pruning.
 - (c) Generate the machining plan (O, C) by mapping each g in G to its associated machining operation o (o consists of op(g) plus the recommended machining parameters taken from a machining data handbook such as [53]), and applying the precedence constraints C to the machining operations.
 - (d) If any face of the part involves tight surface finish/tolerance(s), then augment (O, C) by incorporating finishing operation(s) to improve that face. Section 7.3.3 describes this step in detail.
 - (e) Call Evaluate-Mach-Accr(O, C). This procedure estimates the achievable tolerances for the operation plan (O, C). Details of this procedure are described in Chapter 8.

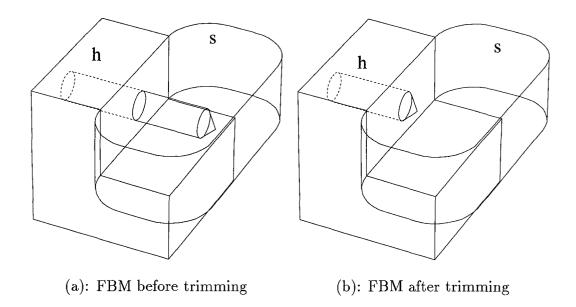


Figure 7.10: An example of FBM trimming.

- (f) If (O, C) is capable of meeting the design tolerances then compute the rating for the machining plan (O, C). Details of this procedure are described in Chapter 8.
- (g) If (O, C) is better than the current-best machining plan, then update the current-best machining plan. Otherwise, discard (O, C).

7.3.1 Trimming of Unuseful Portions of Features in FBMs

As described in Chapter 5, the feature identification procedure returns primary features. Since FBMs are formed from these primary features, the removal volumes of various features may sometimes intersect. If two features have intersecting removal volumes, then machining either of them will remove the shared volume. However, in the case of certain types of features, the bottom portions of the features might not be useful in any machining plan. For example, if a

drilling operation is used to create a through hole, then the bottom portion of the drilling feature does not create any portion of the part boundary. An example of such situation is shown in Figure 7.10(a). In this case, the portion of the drilling feature that intersects with the end milling feature is redundant and not required in any machining plan. Features whose bottom portion may not be useful in any machining plan are called *trimmable* features. In an FBM, it may be possible to modify the trimmable features by modifying it to remove some or all of the shared volume, so as to avoid machining the shared volume twice. Trimming only eliminates the bottom portion of the feature without affecting its datum point or approach face (if possible, remaining portions get truncated in Step 4c of Generate-Plan procedure). As described in Section 7.3, the procedure Generate-Plans determines the precedence constraints by examining the significant intersection among the features. Trimming eliminates unnecessary intersection among the features. Thus in order to improve the computation efficiency, the first step in GENERATE-PLANS is to trim the features in the FBM F wherever it can. Details of the procedure for this task are described below.

procedure TRIM-FBM(F)

For every trimmable $f \in F$, do the following:

- (a) Let r be the portion of f's removal volume that is not shared by any other feature, i.e., $r = (\text{eff}(f, S) {}^* \cup_{g \in F \{f\}} (\text{rem}(g)).$
- (b) Find the *smallest* feature h that satisfies following conditions:
 - i. h and f have the same machining operations (i.e., op(h) = op(f)).
 - ii. h and f have the same orientation vector (i.e., $\vec{v}(h) = \vec{v}(f)$).
 - iii. h and f have the same datum points (i.e., $p_d(h) = p_d(f)$).

- iv. h and f have the same approach face (i.e., a(h) = a(f)).
- v. h can remove the volume r (i.e., $eff(h, S) \supseteq r$).
- (c) Replace f by h in F.

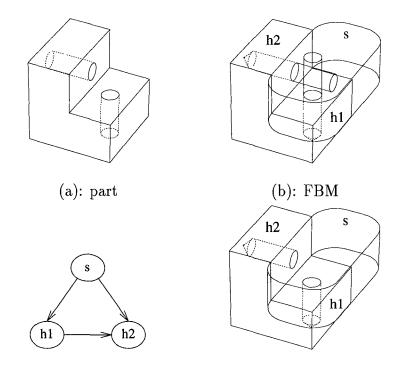
For example, Figure 7.10(b) shows the result of applying the above procedure to the FBM shown in Figure 7.10(a).

7.3.2 Relaxing Redundant Precedence Constraints

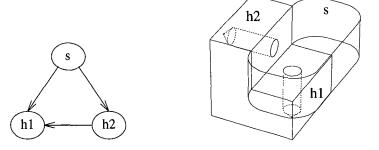
Step 2 of the procedure Generate-Plans may generate feature covers with identical features but different precedence constraints. In such cases, it is possible to combine the sets of precedence constraints into a single set by relaxing the conflicting precedence constraints. For example, suppose that after Step 2, we get two ordered feature covers (G, C) and (G, C') containing the same feature cover G, such that C contains a precedence constraint $g_1 \to g_2$, and C' contains the precedence constraint $g_2 \to g_1$. Then both of these precedence constraints are unneeded, and can be removed from C and C'.

The precedence constraint $g_1 \to g_2$ is not needed for ensuring accessibility in the machining plan resulting from (G,C), because g_2 was accessible before g_1 in (G,C'). The precedence constraint $g_1 \to g_2$ is not needed for ensuring approachability in the machining plan resulting from (G,C), because g_2 was approachable before g_1 in (G,C'). The precedence constraint $g_1 \to g_2$ is not needed for ensuring feature minimality in (G,C), because (G,C') was generated by truncating g_2 before g_1 , and it did not result in any smaller feature than g_2 .

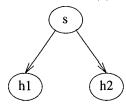
Therefore, the precedence constraint $g_1 \to g_2$ is not needed in (G, C). Similarly, the precedence constraint $g_2 \to g_1$ is not needed in (G, C').



(c): precedence constraints set 1 (d): resulting feature cover



(e): precedence constraints set 2 (f): resulting feature cover



(g): relaxed precedence constraints set

Figure 7.11: An example of precedence constraint relaxation

Step 3 of Generate-Plans takes advantage of the above property to relax the precedence constraints by discarding conflicting constraints. This is done using the following procedure.

procedure Relax-Prec-Const(\mathcal{G})

- 1. While \mathcal{G} contains ordered FBMs (G, C') and (G, C'') containing the same FBM G but different precedence constraints (i.e., $C' \neq C''$), do the following:
 - (a) Let C be the set of precedence constraints consisting of those precedence constraints that are common in C' and C'' (i.e., $C = C' \cap C''$).
 - (b) Replace (G, C') and (G, C'') in \mathcal{G} by (G, C).

2. Return \mathcal{G} .

For example, Figure 7.11(b) shows an FBM for the part shown in Figure 7.11(a). Figures 7.11(c) and (e) show two different sets of precedence constraints for this FBM. As shown in Figures 7.11(d) and (f), truncating this FBM using either set of precedence constraints results in the same feature cover. Thus, the precedence constraints among h1 and h2 are redundant and are removed. Figure 7.11(g) shows the relaxed set of precedence constraints.

7.3.3 Incorporating Finishing Operations

Step 6(d) of GENERATE-PLANS involves incorporating finishing operations to create the faces that have tight surface finish/tolerance(s). Whenever a finishing operation is added, the precedence constraints are updated in such a way that the finishing operation succeeds the roughing operation that creates the face to

which the finishing operation is applied. The cutting parameters of the finishing operation are selected based on the surface finish of the face. In this thesis, only one finishing operation per face is allowed. For cylindrical surfaces, reaming is considered to be the only available finishing operation.

7.3.4 Example

Figure 7.13(b) shows a trimmed FBM for the bracket shown in Figure 7.12. Figure 7.13(c) shows the intersection graph for the trimmed FBM. Each edge in this graph represents a significant intersection between two features. Figure 7.14 shows the results produced by various steps of GENERATE-PLAN on the FBM shown in Figure 7.13(a). As shown in the figure, Step 4 produces two identical feature covers. Therefore, in Step 5, GENERATE-PLAN relaxes the precedence constraints $s3 \rightarrow h2$ and $h2 \rightarrow s3$, producing the ordered feature cover shown in the bottom portion of the figure. Because of the cylindrical stock boundary, if the hole h1 is machined before the slot s1, then h_1 's entry face will be a curved surface and will pose an approachability problem. Therefore, procedure GENERATE-PLANS generates no ordered feature cover in which $h1 \rightarrow s1$. The detailed machining plan generated from the FBM shown in Figure 7.13(a) is shown in Figure 7.15. The bracket shown in Figure 7.12 did not involve any face with tight surface finish/tolerances. Thus, no finishing operations were added to the plan.

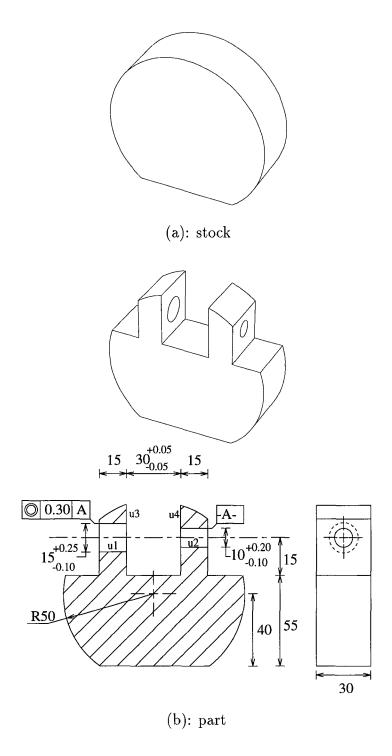
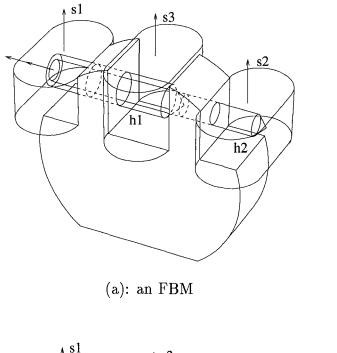


Figure 7.12: A swivel bracket.



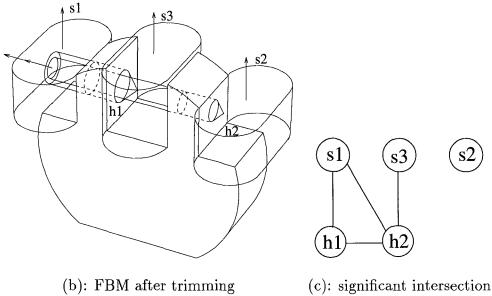


Figure 7.13: A trimmed FBM for the swivel bracket shown in Figure 7.12.

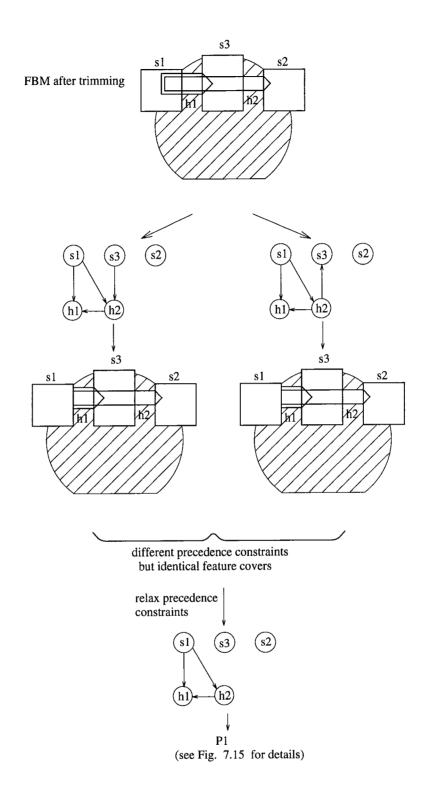


Figure 7.14: Generating machining plans from the FBM shown in Figure 7.13.

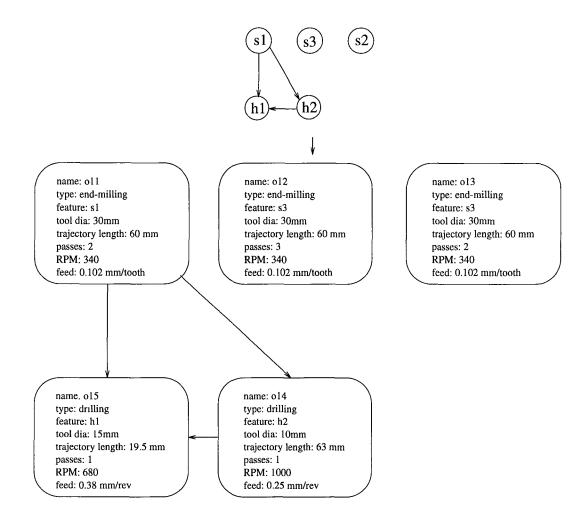


Figure 7.15: Details of Machining Plan P1.

7.4 Discarding Unpromising Machining Plans

Various heuristics techniques are used in GENERATE-PLANS procedure to discard the ordered feature covers that lead to unpromising machining plans. Section 7.4.1 describes the pruning techniques that are used to prune the ordered feature covers that involve infeasible machining operations which violate common machining practices. Section 7.4.2 describes the pruning techniques to discard the ordered feature covers that pose problems for fixturing.

7.4.1 Identifying Infeasible Machining Operations

When primary features are identified, all of the constraints that are associated with the features cannot be evaluated. During the generation of machining plans, after trimming and truncation, various features are evaluated to determine the possible violation of common machining practices. A feature will result in an infeasible machining operation if any of the following types of problems are encountered.

- 1. Accessibility problems. If the accessibility volume of any feature intersects with the workpiece, then the ordered feature cover is considered unpromising. An example of an accessibility problem is shown in Figure 7.16.
- 2. **Approachability problems.** If any feature is not approachable in the workpiece, then the ordered feature cover is considered unpromising. An example of an approachability problem is shown in Figure 7.17.
- 3. Violation of dimensional constraints. Depending upon the availability of machining resources (i.e., cutting tools, machine tools, fixtures), various

features modeling different machining operations are assigned dimensional constraints. Examples of such dimensional constraints include length to diameter ratio for drilling operations, maximum and minimum diameters of various cutting tools, and maximum depth for milling operations. If any feature violates any dimensional constraint, then the ordered feature cover is considered unpromising. Figure 7.18 shows an example of violation of dimensional constraint. In this case, the length/diameter for drilling feature h2 exceeds the permissible limit.

7.4.2 Fixturability-Based Pruning

Fixturability analysis is out of the scope of this thesis. However, fixturability-based pruning has been incorporated into GENERATE-PLANS to illustrate how this information can be used to discard unpromising feature covers. Currently, the flat-jaw vise is considered to be the only available fixturing device.

In order to start the machining process, the stock needs to be properly fixtured. Any given stock can be fixtured such that only a limited number of approach directions can be used for machining. For example, if a vice is the only fixturing device, a cylindrical stock can only be clamped along its two flat end faces. Any vector that is parallel to these flat faces is a valid starting approach direction. However, no machining operation with an orientation vector perpendicular to these flat faces can be used as a starting approach direction. As machining proceeds, new surfaces are created and some of these surfaces can be used for fixturing in subsequent operations. However, in order to start machining, at least one feature with no predecessors should have an orientation vector that matches at least one of the starting approach directions.

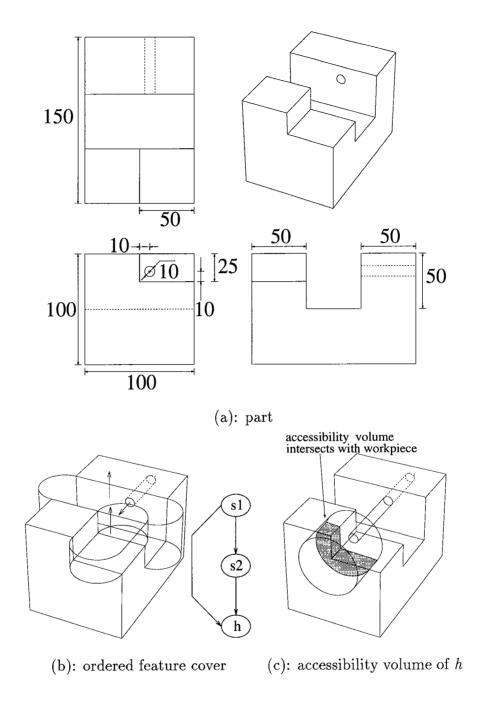


Figure 7.16: An example of a violation of an accessibility condition. h cannot be drilled as shown in the figure, because h's accessibility volume will intersect with the workpiece. Thus, GENERATE-PLAN would discard this feature cover, and try a different feature cover for the part.

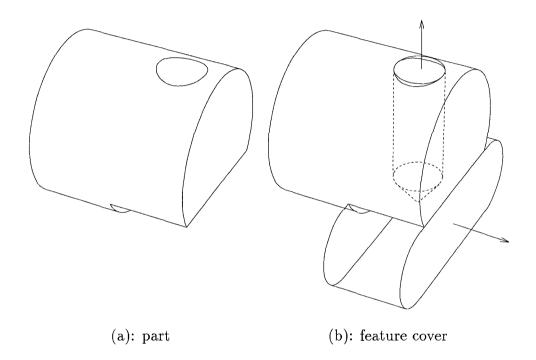


Figure 7.17: An example of a violation of an approachability condition. In this feature cover, the entry face for the hole h is not planar. Thus, GENERATE-PLAN would discard this feature cover, and try a different feature cover for the part.

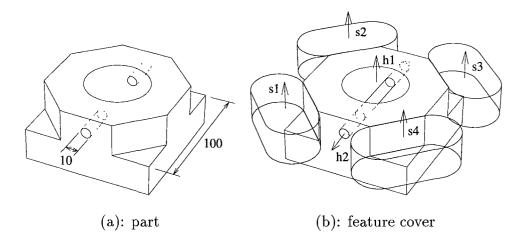


Figure 7.18: An example of a violation of a dimensional constraint. In this feature cover, h2 cannot be drilled because its length/diameter ratio is greater than 8. Thus, GENERATE-PLAN would discard this feature cover.

Fixturability based pruning is performed using a vice as the clamping device.

The following procedure is used to prune the ordered feature covers that are considered unpromising on the basis of fixturability considerations.

- 1. Initialize $X = \emptyset$ (set X will be used to store the possible clamping directions for the stock).
- 2. Let U be the set of all pair of parallel planar faces on the stock.
- 3. For every pair of faces (u, u') in U, do the following.
 - (a) Let \vec{x} be a vector perpendicular to u and u'.
 - (b) Add \vec{x} to X.
- 4. If there is no feature f having no predecessor in the ordered feature cover G such that $\vec{v}(f)$ is perpendicular to some vector in X, then G is unpromising.

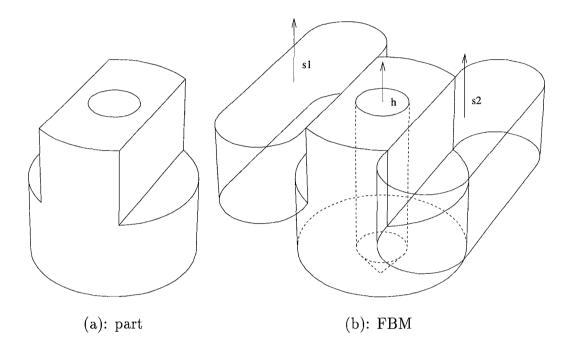


Figure 7.19: An example of fixturability based pruning. For this feature cover, there is no way to hold the workpiece using a flat-jaw vise. Since GENERATE-PLAN does not consider any other kind of fixturing, it would discard this feature cover and try a different feature cover for the part. If vee-jaw vise was being considered as well, then this feature cover would not be discarded.

This pruning technique is quite effective in the case of cylindrical stock, and it prunes many unpromising feature covers. For example, consider the part shown in Figure 7.19(a) that needs to be machined from a cylindrical stock. A feature cover for this part is shown in Figure 7.19(b). Since all the features in this feature cover have orientation vectors perpendicular to the two flat faces of the stock, the stock cannot be held in a flat-jaw vise and this feature cover is unpromising.

Chapter 8

Evaluation of Machining Plans

After generating a machining plan, the next step is to evaluate the machining plan. This step corresponds to Step 4(b) of the overall approach shown in Figure 1.2. Evaluation of a machining plan is done in two stages. The first stage verifies whether or not the machining plan is capable of meeting the design tolerances. Section 8.1 describes the procedure developed in this thesis for this task. If the plan is capable of meeting the design tolerances, then the second stage of plan evaluation is performed. Otherwise, the plan is discarded. The second stage evaluates the rating of the plan. Section 8.2 describes the procedure developed in this thesis for this task.

8.1 Estimating Machining Accuracy

Each machining operation creates surfaces that have certain geometric variations compared to their nominal geometry. Designers normally give design tolerance specifications on the nominal geometry, to specify how large these variations are allowed to be without violating the functionality requirements. To verify whether or not a given machining plan will produce the desired design tolerances, we want

to estimate what tolerances the machining plan can achieve.

The approach developed in this thesis is restricted to the tolerances on planar and cylindrical surfaces. Moreover, in the case of geometric tolerances, only regardless of feature size (RFS) type of tolerances are handled.

Each machined surface has the following three associated accuracy characteristics:

- 1. A form error, ϵ_f . For planar surfaces this error is the flatness of the machined surface, and for cylindrical surfaces is the cylindricity of the machined surface.
- 2. A dimensional variation, ε_d. This defines the dimensional zone with respect to the nominal (ideal) surface in which the machined surface lies. For planar surfaces, this zone is defined by two planar surfaces parallel to the nominal surface, and for cylindrical surfaces, it is defined by two cylindrical surfaces concentric with the nominal surface. For planar surfaces ε_d is defined by the width of dimensional zone that is considered to be distributed equally on each side of the nominal surface. In case of cylindrical surfaces, ε_d is defined by two components ε_d⁺ and ε_d⁻. These components describe the radial distance between the nominal surface and the cylindrical surfaces that define the dimensional variation.
- 3. A surface finish, ϵ_s . This describes the smoothness (or roughness) of the machined surface. Three main indices are used to characterize the surface finish: root mean square (RMS) roughness; arithmetic roughness average; and peak-to-valley roughness height [53]. Arithmetic roughness average is recommended by the ANSI Y14.36 standard and will be used in this thesis.

Table 8.1: Tolerance table for the bracket shown in Figure 7.12.

surface(s)	tolerance type	value(s)
u1	diameter	+0.25, -0.10
u2	diameter	+0.20, -0.10
(u3, u4)	length	+0.05, -0.05
(u1, u2)	concentricity	0.30

For some machining operations, the actual datum point is different from the desired datum point. This error is referred to as the location error, ϵ_l . For example, in the case of drilling operations, the center of a drilled hole is quite often different from the nominal (ideal) location. In this thesis, location errors will be used for various machining operations that are used to create holes (i.e., complete cylindrical surfaces). Section 8.1.3 provides sample machining accuracy data for various machining operations on a 3-axis vertical machining center.

8.1.1 Procedure for Comparing Estimated Machining Accuracy with Design Tolerances

In order to verify whether a machining plan is capable of meeting the design tolerances or not, the estimated machining accuracy is compared with the design tolerances. First, from the set of tolerance attributes of the part, a tolerance table is constructed that describes various tolerances as attributes of various surfaces. Table 8.1 shows the tolerance table for the bracket shown in Figure 7.12. As shown in Table 8.1, a tolerance table has two types of entries: tolerances associated with a single surface, and tolerances associated with a pair of surfaces. After constructing the tolerance table, the following procedure is used to compare

the estimated machining accuracy with the design tolerances.

procedure EVALUATE-MACH-ACCR(O, C)

- 1. Let $\{o_1, o_2, \ldots, o_n\}$ be a total order of the operations in O that is consistent with precedence constraints in C.
- 2. For i > 0, if o_i creates any face u which appears in the tolerance table, then calculate the form error ϵ_f , dimensional variation $\epsilon_d^+, \epsilon_d^-$, surface finish ϵ_s , and location error ϵ_l associated with u. Let $E(u) = \{\epsilon_f, \epsilon_d^+, \epsilon_d^-, \epsilon_s, \epsilon_l\}$. If a face is created by a roughing operation and later improved by a finishing operation, then E(u) for that face is based on the finishing operation.
- 3. For every tolerance-table entry that involves a single face u, do the following:
 - (a) Calculate the achievable tolerance from E(u) (formulas for calculating the tolerances are described in Section 8.1.2).
 - (b) If the achievable tolerance does not satisfy the design tolerance, then return failure.
- 4. For every tolerance-table entry that involves a pair of faces u and u', do the following:
 - (a) Calculate the achievable tolerance from E(u) and E(u'), using different setups for u and u'.
 - (b) If the achievable tolerance does not satisfy the design tolerance, then add (u, u') to the set \mathcal{U} . \mathcal{U} contains pairs of features whose tolerance is tight enough that it cannot be achieved in different setups.

- 5. If there is no way to order the operations in O consistently with C such that the operations associated with every pair $(u, u') \in \mathcal{U}$ can be done in a single setup, then return failure.
- 6. For every $(u, u') \in \mathcal{U}$, do the following:
 - (a) Calculate the achievable tolerance from E(u) and E(u') assuming the same setup for u and u'.
 - (b) If the achievable tolerance does not satisfy the the design tolerance, then return failure.
- 7. Return success (note that this will occur only if Steps 3(b), 5 or 6(b) do not return failure).

If the machining plan is capable of meeting the design tolerances, then this procedure returns success. Otherwise, this procedure returns failure.

8.1.2 Calculating Geometric and Dimensional Tolerances

In Steps 3(a), 4(a), and 6(a) of the procedure EVALUATE-MACH-ACCR, achievable tolerances are computed from the estimated machining accuracy data. This section describes formulas for calculating various tolerances.

Diameter Tolerances. Diameter tolerance is directly derived from the dimensional variation of the cylindrical face. Let u be a cylindrical face, and let $(\epsilon_d^+, \epsilon_d^-)$ be the two component of dimensional variation associated with u. The diameter tolerance on u is calculated as

upper limit =
$$\epsilon_d^+$$

lower limit
$$= \epsilon_d^-$$
.

Length Tolerances. Let u1 and u2 be two parallel planar faces. Let ϵ_{d1} and ϵ_{d2} be the dimensional variations associated with u1 and u2 respectively. Then the length tolerance between u1 and u2 is calculated as

upper limit =
$$0.5 \times (\epsilon_{d1} + \epsilon_{d2} + \text{error due to setup change})$$

lower limit = $-0.5 \times (\epsilon_{d1} + \epsilon_{d2} + \text{setup error})$.

Form Tolerances. Form tolerances such as cylindricity or flatness are directly derived from the form error ϵ_f . Let u be a face and let ϵ_f be the form error associated with u. The form tolerance associated with u is calculated as

form tolerance =
$$\epsilon_f$$
.

Concentricity Tolerances. Let u1 and u2 be two cylindrical faces. Let ϵ_{l1} and ϵ_{l2} be the location errors associated with the datum points of u1 and u2 respectively. Then the concentricity tolerance between u1 and u2 is calculated as

concentricity tolerance =
$$\epsilon_{l1} + \epsilon_{l2} + \text{setup error}$$
.

Positional Tolerances. Let u be a cylindrical face whose axis has been assigned a position tolerance. Let ϵ_l be the location associated with u. Let u_{d1} and u_{d2} be two mutually perpendicular datum surfaces that are parallel to the axis of u. Let ϵ_{d1} and ϵ_{d2} be the dimensional variation associated with u_{d1} and u_{d2} respectively. The position tolerance for u is calculated as

position tolerance =
$$\epsilon_l + \sqrt{\epsilon_{d1}^2 + \epsilon_{d2}^2}$$
.

Angularity, Parallelism and Perpendicularity Tolerances. Let u1 and u2 be two planar faces. Let ϵ_{d1} and ϵ_{d2} be the dimensional variations associated with u1 and u2 respectively. Then the angularity/parallelism/perpendicularity tolerance between u1 and u2 is calculated as

angularity/parallelism/perpendicularity tolerance = $\epsilon_{d1} + \epsilon_{d2} + \text{setup error}$.

Errors Due To Setup Changes. The actual value of the error due to a setup change depends on the way a workpiece is fixtured in the machine tool. Fixturability analysis is not performed in this thesis, thus the error due to setup change cannot be estimated accurately. Instead, a constant value of setup error will be used. The setup error is assumed to be 0 if the operations associated with the two faces are done in the same setup. If two faces are machined in different setups, then the setup error is calculated as follows. If the face being machine first is planar and the plane containing that face does not intersects with the interior of the part, then the setup error is assumed to be 0 (a face satisfying this condition can be used for establishing the datum for machining of the second face). Otherwise, the setup error is assumed to be 0.20mm. However, it should be noted that if the results of fixturability analysis were available, it would be quite straightforward to use those estimates of setup errors in all of the above formulas.

8.1.3 Machining Accuracy Data

Each machining operation creates surfaces with different characteristics. This section presents the sample machining accuracy data for various machining operations performed on 3-axis vertical machining centers. Most of this data is

Table 8.2: Machining accuracy data for drilling.

diameter range	dimensional variation		form error	surface finish
(mm)	$\epsilon_d^+ \text{ (mm)} \epsilon_d^- \text{ (mm)}$		(mm)	$(\mu \mathrm{m})$
3 to 6	0.100	0.025		
6 to 13	0.150	0.025		
13 to 25	0.200	0.050	0.100	1.6
25 to 50	0.250	0.080		
50 to 100	0.300	0.100		

Table 8.3: Location errors for drilling.

drilling condition	location error
drilling a new hole	0.15mm
enlarging a pre-existing hole	0.10mm

applicable for plain carbon steels and has been compiled from [8, 11, 86, 53].

Drilling. Table 8.2 presents machining accuracy data for cylindrical surfaces produced by drilling operations. In the case of drilling operations, typically the center of the hole is away from its nominal location. Table 8.3 gives the data for location errors in drilling operations.

Reaming. Table 8.4 presents machining accuracy data for cylindrical surfaces improved by reaming operations. Reaming operations do not improve any previous location errors. Thus after reaming, the location error is assumed to be the same as left by the previous operation.

Table 8.4: Machining accuracy data for reaming.

diameter range	dimensional variation		form error	surface finish
(mm)	$\epsilon_d^+ (\mathrm{mm})$	$\epsilon_d^- (\mathrm{mm})$	(mm)	$(\mu \mathrm{m})$
5 to 12	0.012	0.0		
12 to 25	0.025	0.0		
25 to 50	0.050	0.0	0.010	0.8
50 to 100	0.075	0.0		

Face-Milling. Table 8.5 presents machining accuracy data for planar surfaces produced by rough face-milling operations. Table 8.6 presents machining accuracy data for planar surfaces improved by finish face-milling operations. Surface finish for face milling operations depends on the feed. Table 8.7 shows surface finish data for face-milling operations.

End-Milling. Table 8.8 presents machining accuracy data for planar surfaces produced by end-milling operations. For end-milling operations, surface finish data is same as face-milling surface finish data.

Side-Milling. For side-milling operations, the machining accuracy data is same as face-milling machining accuracy data.

8.1.4 Examples

Consider the bracket shown in Figure 7.12. Table 8.1 shows the tolerance table for this part. Let us assume that this part will be machined on a 3-axis vertical machining center. A machining plan P1 for this part is shown in Figure 7.15. P1 is capable of meeting the design tolerances for this part. Both the tolerances on

Table 8.5: Machining accuracy data for rough face-milling.

dimensional variation	form error
(mm)	(mm)
0.050	0.050

Table 8.6: Machining accuracy data for finish face-milling.

dimensional variation	form error
(mm)	(mm)
0.025	0.025

Table 8.7: Surface finish data for face-milling.

feed	roughness average	
(mm/tooth)	$(\mu \mathrm{m})$	
0.02	0.43	
0.04	0.85	
0.06	1.3	
0.08	1.7	
0.10	2.1	
0.12	2.6	

Table 8.8: Machining accuracy data for end-milling.

dimensional variation	form error		
(mm)	(mm)		
0.100	0.040		

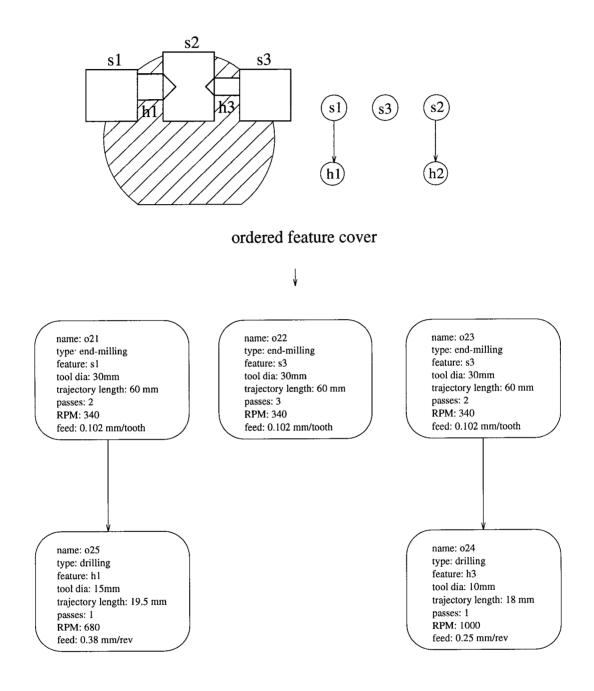


Figure 8.1: Machining plan P2 for the bracket shown in Figure 7.12.

the hole diameters can be easily achieved by drilling operations o14 and o15 in P1. In P1, the length tolerance between u3 and u4 can be easily achieved since they are created by the end-milling operation o12. In P1, drilling operations o14 and o15 that create u1 and u2 have the same approach direction. Thus, these operations can be performed in the same setup, and are capable of achieving the concentricity tolerance between u1 and u2.

Now consider the machining plan P2 shown in Figure 8.1. This plan fails to meet the design tolerances. Though this plan is capable of achieving the tolerances on the hole diameters, and length tolerance. But the drilling operations o24 and o25 have different approach directions in P2. This introduces setup error in calculation of concentricity tolerance. Thus, this plan fails to meet the concentricity tolerance between u1 and u2.

8.2 Computing Production Time Based Plan Ratings

One can use production cost, production time, or a combination of production cost and time to rate the machining plans. Several components of production cost, such as prevailing wages, depreciation of equipment and so forth, vary significantly from industry to industry. Thus, quite often it is very difficult to have access to reliable data on the production cost. Thus, in this thesis, estimated production time is used to rate machining plans. The plan rating R_P is defined as

$$R_P(O,C) = PT(O,C),$$

where PT is estimated production time. O is the set of machining operations in

the plan. C is the set of precedence constraints on operations in O. However, it should be noted that in a specific industrial environment where reliable cost data is available, the approach developed in this thesis can be easily extended to incorporate production cost in the machining plan ratings.

The production time mainly consists of three main components: the machining time, auxiliary time, and setup time. The machining time is the portion of the production time that is actually spent in machining (when the tool engages in cutting). The auxiliary time is the portion of the production time that is spent on various auxiliary activities, such as tool changes and rapid tool movements during cutting. The setup time is the portion of the production time that is spent in fixturing the workpiece on the machine tool. For a given machining plan (O, C), the estimated production time PT is given by the following formula:

$$PT(O,C) = \text{machining time} + \text{auxiliary time} + \text{setup time}.$$

In this thesis, the auxiliary time is approximated by a fixed fraction of the machining time. Thus, the estimated production time is approximated by

$$PT(O,C) = (1+\beta) \times \sum_{o \in O} T_m(o) + \text{setup time},$$

where β is the fraction of machining time that accounts for the auxiliary time, and T_m is the estimated machining time. In this thesis, $\beta = 0.25$ is used.

Section 8.2.1 describes the details of a procedure for estimating machining time. Section 8.2.2 describes the details of a procedure for estimating the setup time. Section 8.2.3 presents an example of computing the machining plan rating.

8.2.1 Estimating Machining Time

The machining time T_m for a machining operation o is given by

 $T_m(o) = \text{estimated trajectory length} \times \text{number of passes}/f,$

where f is feed in mm/minute. Typically, feed is given in mm/rev for drilling operations, and mm/tooth for milling operations. This value of feed is multiplied by the RPM value (and if needed, the number of tool teeth) to get the feed value in mm/minute.

For each type of the machining operations, the trajectory length is estimated by the parameters of its machining feature. For certain kinds of machining operations, it is straightforward to estimate the trajectory length. For example, in case of drilling, reaming, face-milling, straight end-milling, and slot milling operations the trajectory length is equal to the length of the feature. In case of an arbitrary shaped milling profile, the correct value of trajectory length can be estimated by generating the cutter path. However, generation of the cutter path is computationally very expensive. Thus in this thesis, the trajectory length is estimated through an indirect procedure.

Relating the Area Swept by a Circle to the Space Curve Length: Let us consider a parameterized space curve t. Let us sweep a circle of diameter D along this space curve by an incremental distance ds (as shown in Figure 8.2). The swept area is given by

$$dA = 0.25 \times \pi D^2 + Dds$$
.

Let us assume that the space curve t is such that the swept area is non-self-intersecting. In this case, the swept area generated by sweeping the circle along the complete space curve is given by

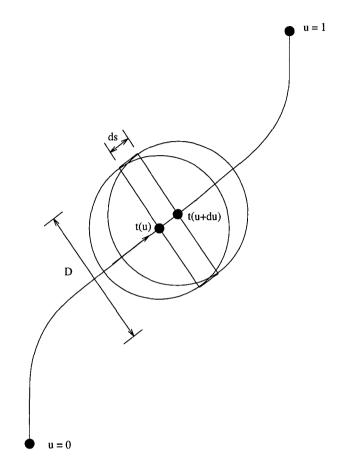


Figure 8.2: Sweeping a circle along a space curve.

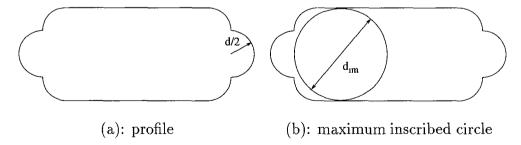


Figure 8.3: Correction for multi-cutter machining.

$$A = \int_{u=0}^{u=1} dA$$

= $0.25 \times \pi D^2 + D \int_{u=0}^{u=1} ds$.

Note that

$$\int_{u=0}^{u=1} ds = \text{length of the space curve } t$$
$$= l.$$

Therefore,

$$A = 0.25 \times \pi D^2 + lD.$$

From this equation we get

$$l = (A - 0.25 \times \pi D^2)/D.$$

This formula will be used to estimate the trajectory length for arbitrary shaped milling profiles.

Estimation of trajectory length. Sometimes, geometric constraints on a milling profile result in selection of a milling tool with a very small diameter. For example, Figure 8.3(a) shows a profile that results in selection of a very small cutter. In practice, such milling profiles are machined by more than one cutters. A bigger tool is used to machine most of the material inside the profile, followed by the smaller tool that creates the final profile. For example, in case of the profile shown in Figure 8.3(a), a tool of diameter d_{im} (as shown in Figure 8.3(b)) can be used to machine most of the portion of the profile, and finally a tool of

diameter d can be used to create the final profile. In order to correctly estimate the trajectory length, the possibility of multi-cutter machining needs to taken into the account.

Let us consider a milling profile P. Let l_c be the sum of the lengths of the closed edges in P. Let A_P be the area of P. Let d be the tool diameter selected for P. The cutting tool will be moved along closed edges to create the final profile. The area swept by the cutting tool when moving along the closed edges can be approximated by dl_c . Based on the values of dl_c and A_P , the following two cases are used to estimate the trajectory length.

Case 1: $dl_c \geq A_P$. In this case, the estimated trajectory length is given by

estimated trajectory length =
$$(A_P - 0.25 \times \pi d^2)/d$$
.

If P is a closed-pocket profile, then $\alpha \times depth$ of the milling pass is added to the estimated cutting trajectory length to account for the plunge-in cut. α is a factor that accounts for the slow feed rate for plunge-in cuts. Typically, value of α depends on the tool diameter and the depth of plunge-in cut. In this thesis $\alpha = 3$ will be used.

Case 2: $dl_c < A_P$. In this case the possibility of multi-tool machining is considered and the following formula is used

estimated trajectory length
$$= (A_P - 0.25 \times \pi d_m^2)/d_m + l_c$$

where $d_m = \min (d_{tm}, d_{im})$. d_{im} is the diameter of the maximum inscribed circle in the profile P. d_{tm} is the maximum allowable tool diameter. If P

is a closed-pocket profile, then $\alpha \times \text{depth}$ of the milling pass is added to the estimated cutting trajectory length to account for the plunge-in cut.

It should be noted that in this thesis no attempt is made to optimize the values of cutting parameters. Thus, in some cases, the estimates of machining time may involve considerable approximation. However, the machining plan ratings are only used to assess the manufacturability of designs during early design stages. Thus, such approximation results in acceptable manufacturability ratings.

8.2.2 Estimating Setup Time

Estimation of setup time involves determining the exact setup sequence and estimating the time associated with each of the setups in the sequence. Thus, the formula for setup time estimation is given by

setup time
$$=\sum_{i=1}^{n}T_{si},$$

where T_{si} is the time associated with the i^{th} setup. The actual value of T_{si} depends on the part geometry and the setup method. A good estimation of T_{si} can be only achieved through setup planning and fixturability analysis. However, fixturability analysis is out of the scope of this thesis. Thus in this thesis, the setup time is estimated based on the average setup time. This approximation results in following formula

setup time =
$$n \times T_s$$
,

where T_s is the average setup time, and n is the minimum possible number of setups.

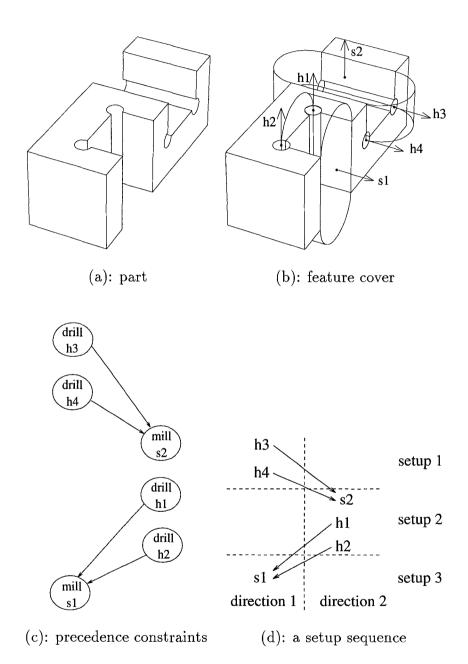


Figure 8.4: An example of setup estimation.

Wilson's handbook [90] gives data for a variety of setup procedures. In this thesis, the average setup time is based on vise clamping. As per Wilson's handbook, for a flat-jaw vise, the fixturing time is between 0.8 to 1.2 minutes depending on the weight of the part. In a vertical machining center, additional time is needed to establish the datum on the workpiece. We add 1.0 minute to the fixturing time to account for establishing the datum.

It should be noted that for a given machining plan (O, C), the minimum number of setups is not necessarily equal to the number of approach directions. In presence of precedence constraints, the minimum number of setups for a given machining plan may be greater than the number of approach directions. For example, consider the part shown in Figure 8.4(a). A feature cover for this part is shown in Figure 8.4(b). Various precedence constraints for this feature cover are shown in Figure 8.4(c). Figure 8.4(d) shows a setup sequence that involves the minimum number of setups. In this case, the number of approach directions is two but the minimum possible number of setups is three.

A depth-first branch-and-bound procedure is used to determine the setup sequence with the minimum possible number of setups. As described below, FIND-SETUP-SEQUENCE initializes the global variable S to the setup sequence in which every operation in O is performed in different setup, and calls EXTRACT-SETUP. EXTRACT-SETUP updates value of S as it finds better setup sequences. EXTRACT-SETUP takes three arguments: O, the set of remaining machining operations; C, the set of precedence constraints on operations in O; and S_i , the setup sequence so far. EXTRACT-SETUP chooses an approach direction in O such that there is at least one operation with no predecessors in that approach direction. All the operations in that approach direction that can be machined

in the same setup are extracted and a new setup is created. This new setup is added to S_i and EXTRACT-SETUP is called recursively with the remaining operations and an updated S_i to find new setups. If all operations in O have been incorporated in some setup, and the number of setups is less than the least number of setups so far, then the best setup sequence is updated. If any setup sequence in the search-space results in greater number of setups than the number of setups in the best setup so far, then that sequence is pruned. Whenever more than one approach direction can be selected, all of the possibilities are tried. The efficiency of EXTRACT-SETUP depends on the order in which it examines the approach directions in V. The heuristic used here is to iterate over the approach directions in V in the order of decreasing cardinality of SETUP(\vec{v}).

procedure FIND-SETUP-SEQUENCE(O, C)

- 1. Initially, let $S = \{\{o_1\}, \{o_2\}, \dots \{o_n\}\}$. Note that S will be updated by EXTRACT-SETUP.
- 2. Call Extract-Setup(O, C, \emptyset).
- 3. Return number of setups in S.

procedure EXTRACT-SETUP (O, C, S_i)

- 1. If S_i has more number of setups than S, then return, because the number of setups exceeds the best solution so far.
- 2. Otherwise, if $O = \emptyset$, then we have found a better solution, so set $\mathcal{S} = \mathcal{S}_i$ and return.
- 3. Otherwise,

- (a) Let READY be the set of all operations in O that have no predecessors.
- (b) Let V be the set of all approach directions of operations in READY (i.e., $V = \{\vec{v}(o) : o \in \text{READY}\}$).
- (c) For every $\vec{v} \in V$, let SETUP(\vec{v}) be the set of all operations o in O such that
 - i. o has \vec{v} as its approach direction;
 - ii. either o has no predecessor in O, or all predecessors in O have \vec{v} as their approach direction.

Note that all of these operations can be done in the same setup.

- (d) Let $C_s(\vec{v})$ be the set of precedence constraints that are associated with the operations in SETUP(\vec{v}).
- (e) If there exists a $\vec{v} \in V$ such that there is no operation in the set $O \text{SETUP}(\vec{v})$ that has \vec{v} as its approach direction, then call EXTRACT-SETUP $(O \text{SETUP}(\vec{v}), C C_s(\vec{v}), \mathcal{S}_i \cup \{\text{SETUP}(\vec{v})\})$.
- (f) Otherwise, for every approach direction $\vec{v} \in V$, call EXTRACT-SETUP($O \text{SETUP}(\vec{v}), C C_s(\vec{v}), S_i \cup \{\text{SETUP}(\vec{v})\}$).

For the plan shown in Figure 8.4, the above procedures returns 3 setups as the minimum number of setups.

8.2.3 Example

Consider the plan P1 shown in Figure 7.15. This plan is estimated to require 2 setups. We assume that each setup requires 2.0 minutes. Table 8.9 shows the

Table 8.9: Estimated production time for P1.

Operation	feed	traj. length	passes	T_m	$(1+\beta)T_m, \beta = 0.25$
	(mm/min)	(mm)		(min)	(min)
<i>o</i> 11	140	60.0	2	0.9	1.1
<i>o</i> 12	140	60.0	3	1.6	2.0
<i>o</i> 13	140	60.0	2	0.9	1.1
o14	250	63.0	1	0.4	0.5
<i>o</i> 15	260	19.5	1	.08	0.1

setup time: 4.0 minutes (2 setups)

total time: 8.8 minutes

feed, trajectory length, number of passes, machining time, and auxiliary time for various operations in P1. Total estimated time for P1 is 8.8 minutes. Thus the rating of plan P1 is 8.8 minutes.

Chapter 9

Providing Manufacturability Feedback

After generating and evaluating various machining plans, the next step is to provide manufacturability feedback. This step corresponds to Step 5 of Figure 1.2 which outlines the approach developed in this thesis. Section 9.1 defines the manufacturability rating. Section 9.2 describes the feedback information provided in case of machinable parts. Section 9.3 describes the feedback information provided in case of unmachinable parts.

9.1 Manufacturability Rating

The manufacturability of a given design depends on the following three factors:

- 1. the ability to produce the design within the desired specification;
- 2. the ability to produce the design with a low production cost;
- 3. the ability to produce the design with a low production time.

The first of these factors is handled by examining the realizability of plans and discarding the plans that are not capable of meeting the design specifications. If no realizable plan exists, then the design is considered unmachinable.

If the design can be produced within the desired specifications, then the manufacturability rating can be based on the estimated production cost, production time, or a combination of the two.

In this thesis, plan ratings are used to define the design's manufacturability rating. More specifically, the manufacturability rating M_R of a design is calculated as

 $M_R = \min\{R_P(O,C): (O,C) \text{ is a plan that meets the design specifications}\},$ where R_P is the plan rating.

9.2 Providing Feedback for Machinable Parts

In case of machinable parts the feedback to the designer consists of the following items.

- 1. The machining plan with best rating $(O, C)_o$. The designer can also access all the other plans that are generated during the process of manufacturability analysis.
- 2. The manufacturability rating M_R of the design. As described in Section 9.1, M_R is based on the rating of $(O, C)_o$.
- 3. Production time decomposition for various part faces. This decomposition is based on $(O, C)_o$, and describes the production time associated with various part faces.

In order to compute the production time decomposition in the third item above, first the production time for each machining operation in the plan is calculated. Chapter 8 defines the production time for a machining plan. The production time for a machining operation is defined in a similar manner. It is the sum of the machining time, the auxiliary time, and the setup time. Machining time and auxiliary time for various machining operations can be computed using the procedures described in Chapter 8. The setup time for a machining operation is computed as follows. For the given plan, a setup sequence resulting in the minimum number of setups is generated. For each setup, the setup time is equally distributed to each operation in the setup. Finally, each machined face is assigned the production time of the operation creating the face. If a machining operation creates more than one face, then the production time is assigned to the set of faces created by the operation. If two machining operations create sets of faces with common members, then the production time is assigned to the union of the two sets of faces.

Production time decomposition helps in identifying following two sources of manufacturability problems. First, if a setup involves very few machining operations, then the setup time for each machining operation in that setup is high. Therefore, all the faces created in that setup are associated with high production time. In such situations, the possibility of reorienting the faces with high production time should be explored to eliminate one or more setups. Second, if a face involves tight tolerance or surface finish, it typically requires finishing operations. This results in association of high production cost with such faces. In such situations, the tolerance and surface finish specifications should be reviewed, and the possibility of relaxing the tolerances and surface finishes should be considered.

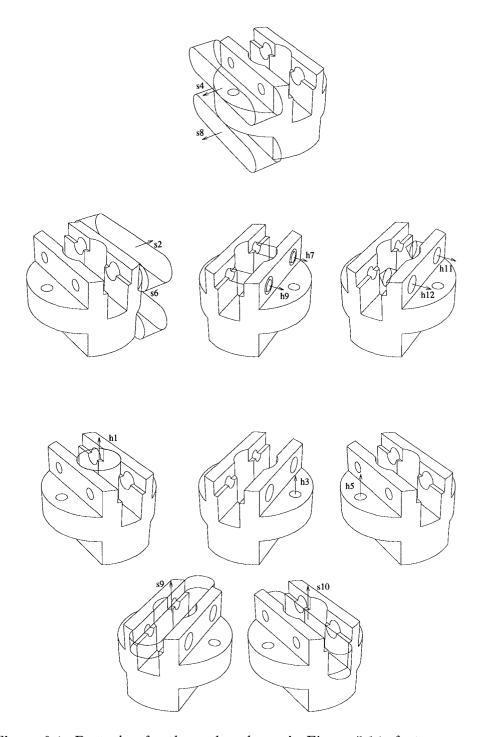
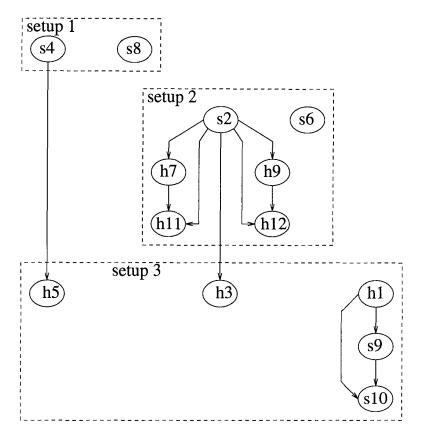


Figure 9.1: Best plan for the socket shown in Figure 5.14: feature cover.



details of machining operations					
feature	type	tool dia	feed	passes	trajectory length
		(mm)	(mm/min)		(mm)
s4	end-milling	50	166	3	225
s8	end-milling	50	166	3	225
s2	end-milling	50	166	3	225
s6	end-milling	50	166	3	225
h7	drilling	20	244	1	106
h9	drilling	20	244	1	106
h11	drilling	30	203	1	39
h12	drilling	30	203	1	39
h1	drilling	75	108	1	172.5
h3	drilling	20	244	1	56
h5	drilling	20	244	1	56
s9	end-milling	50	166	2	250
s10	end-milling	40	207	4	240

Figure 9.2: Best plan for the socket shown in Figure 5.14: details of operations.

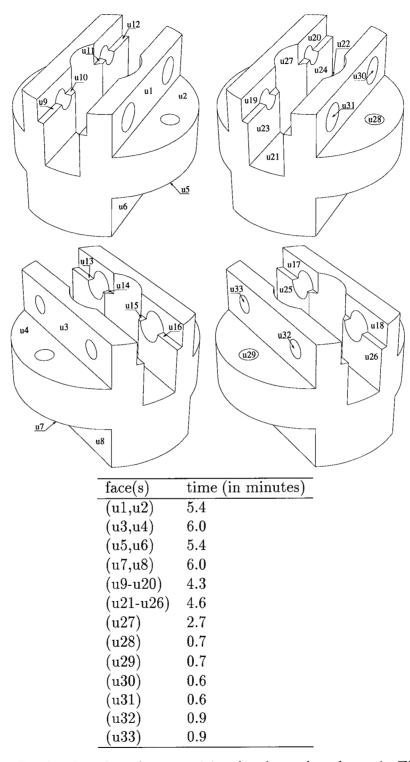


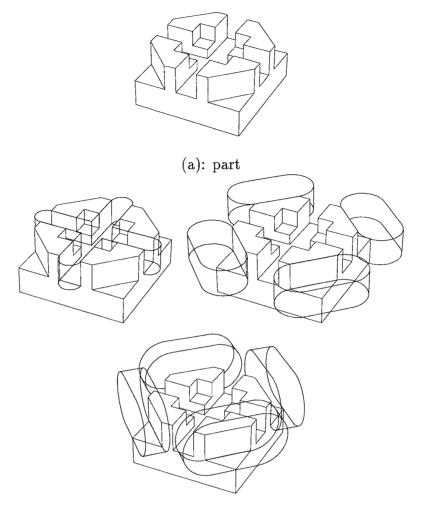
Figure 9.3: Production time decomposition for the socket shown in Figure 5.14.

In many cases, the designer will be designing the parts in terms of functional or design features. In such situations, the production time decomposition for various part faces can easily be translated to various functional features. This translation provides the production time decomposition directly in terms of various functional elements of the design. However, in this thesis, the design is not modeled in terms of functional features. Thus, the production time decomposition has not been calculated in terms of functional features.

The socket shown in Figure 5.14 is machinable on a 3-axis vertical machining center. The manufacturability rating for this part is 39 minutes. Note that several assumptions were made in selecting cutting parameters and estimating setup time, therefore this rating only gives an approximation of estimated production time. Figures 9.1 and 9.2 show the plan with the best rating for this part. Figure 9.3 gives the production time decomposition for various faces that need to be machined.

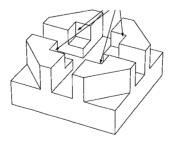
9.3 Feedback for Unmachinable Parts

A part is considered unmachinable, if no machining plan is capable of meeting the design specifications. In this thesis, manufacturability problems are classified into two different types. Section 9.3.1 describes how various shape related manufacturability problems are identified. Section 9.3.2 describes how various dimension and tolerance related manufacturability problems are identified.



(b): the primary feature set

no feature covers these sharp corners



(c): unmachinable portions

Figure 9.4: Example of an unmachinable part shape.

9.3.1 Identifying Shape Related Problems

A design might have shape related manufacturability problems the following two cases.

- 1. There exists a thin section in the design that may deform during machining.

 This type of problem is identified and reported during the preliminary manufacturability analysis. Details and examples of identifying this type of problem are given in Chapter 4.
- 2. There exist portions in the design that cannot be covered by any machining feature. Such portions are identified and reported during design interpretation step (see Chapter 5 for details). For example, Figure 9.4 shows an example of an unmachinable part shape. Figure 9.4(b) shows the primary feature set for the part shown in Figure 9.4(a). Figure 9.4(c) shows the sharp corners that cannot be covered by any machining feature.

9.3.2 Identifying Dimension and Tolerance Related Problems

In some cases, the features in the primary feature set cover the complete delta volume (volume to be machined), but no realizable machining plan can be found. In such situations, the manufacturability problems are related to the design dimensions and tolerances. As various machining plans are generated and evaluated, manufacturability problems can be identified and reported at following different levels.

1. No promising FBM can be found. If a part involves tight tolerances, various features in the primary feature set may have tolerance incompat-

ibility and may not result in any promising FBM (see Section 6.4.3 for details). In this case, various unpromising FBMs along with the potential sources of manufacturability problems are presented to the designer.

- 2. FBMs exist, but no plan with feasible operations can be found. In some cases, FBMs exist. But, various machining operations that are generated from FBMs violate common machining practices resulting in infeasible plans. In this case, various plans along with the potential source of manufacturability problems are presented to the designer.
- 3. Plans with feasible operations exist, but no plan meets the design tolerances. In this case, various plans along with the potential source of problems in meeting the design tolerances are presented to the designer.

Following examples illustrate some of the design dimensions and tolerances that lead to manufacturability problems on a 3-axis vertical machining center. In order to facilitate clearer presentation of the material in this section, very simple examples have been selected.

Example 1. Consider the part shown in Figure 9.5. In this part, the two bottom faces of notches n1 and n2 involve tight parallelism tolerance. The end-milling features corresponding to n1 and n2 have different approach directions. Thus, these end-milling operations cannot be performed in the same setup, and the operations will fail to meet the parallelism tolerance on a 3-axis vertical machining center. In this case, because of tolerance incompatibility between the two end-milling features corresponding to n1 and n2, the only possible FBM for this part is found to be unpromising.

Example 2. Consider the part shown in Figure 9.6. In this part, the two cylindrical faces created by holes h1 and h2 involve tight concentricity tolerance. All FBMs that involve drilling features with different approach directions are unpromising because of tolerance incompatibility. All machining plans that involve drilling features with the same approach direction violate the length/diameter requirement for drilling operations. Thus, there is no feasible plan for this part and this part is unmachinable on a 3-axis vertical machining center.

Example 3. Consider the part shown in Figure 9.7. In this case, machining of pocket p requires an end-milling operation with tool diameter of 4mm. However, due to large depth (75mm) of slot s and a small tool size, this end-milling operation has an accessibility problem. Thus, there is no feasible plan for this part and this part is unmachinable on a 3-axis vertical machining center.

Example 4. Consider the part shown in Figure 9.8. In this part, the side face of step s2 and the side face of slot s1 involve tight perpendicularity tolerance. In order to satisfy the approach condition requirements for the hole h, h should be machined before s1. Moreover, h should be machined after s2. h has different approach direction from s1 and s2. This implies that s1 and s2 cannot be machined in the same setup. Thus, there no plan capable of meeting the perpendicularity tolerance and this part is unmachinable on a 3-axis vertical machining center.

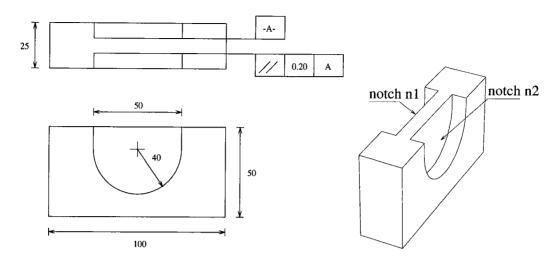


Figure 9.5: A design that would be rejected because its dimensions and tolerances cannot be achieved on a 3-axis vertical machining center (Example 1). However, this design can be machined on a horizontal machining centers.

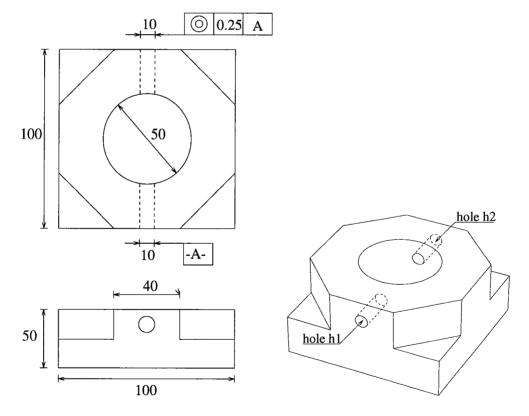


Figure 9.6: A design that would be rejected because its dimensions and tolerances cannot be achieved on a 3-axis vertical machining center (Example 2).

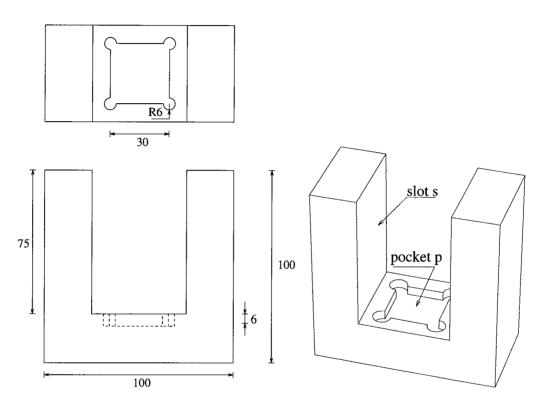


Figure 9.7: A design that would be rejected because its dimensions and tolerances cannot be achieved on a 3-axis vertical machining center (Example 3).

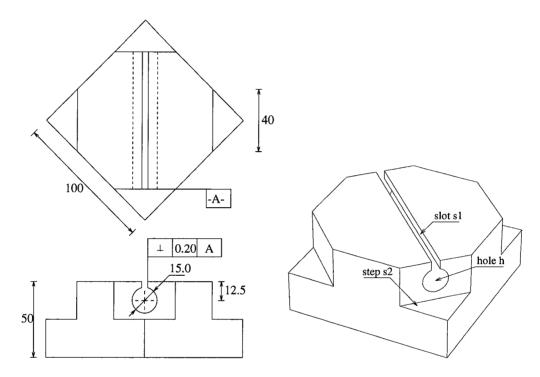


Figure 9.8: A design that would be rejected because its dimensions and tolerances cannot be achieved on a 3-axis vertical machining center (Example 4). However, this design can be machined on a horizontal machining centers.

Chapter 10

Implementation and Examples

To illustrate the approach developed in this thesis, a prototype system called Interactive Manufacturability Analysis and Critiquing System (IMACS) has been implemented. Section 10.1 provides a brief description of IMACS. Sections 10.2.2 and 10.2.3 describe two examples to illustrate the capabilities of IMACS.

10.1 IMACS

10.1.1 Overview

A proof-of-concept implementation of various procedures described in the previous chapters has been done using C++ programming language [21], along with Spatial Technologies' ACIS geometric kernel [81] to perform various solid modeling operations, National Institutes of Health's C++ Class Library [28] to implement various abstract data structures, and Ithaca Software's HOOPS Graphics System [41] to build graphics interface. Figure 10.1 shows the architecture of IMACS.

The implementation of IMACS is modular in nature. Each procedure was

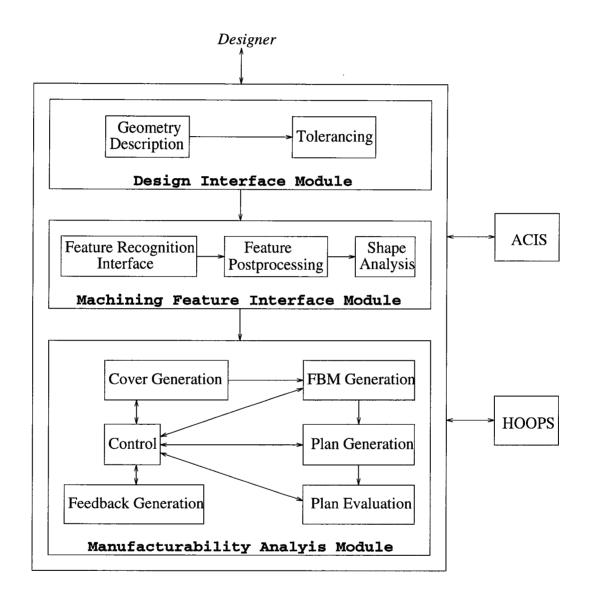


Figure 10.1: Architecture of IMACS.

been implemented independently to allow further augmentation and easy maintenance. There are three main modules in the system. The first module is the design interface that allows the designer to interactively define nominal geometry and tolerance specifications. The second module is the machining feature interface that interacts with the feature recognition system. The third module is the main manufacturability analysis module. The following paragraphs briefly describe each module of the system.

The design interface module has two main submodules. The first submodule is for creating the nominal geometry description. The ACIS Test Harness is used for this purpose. The designer interacts with the Test Harness using a command line interface. The designer can type simple descriptive English language commands to create the solid model of the design. He/she can also create solid models by using the Test Harness script file, a file containing the Test Harness commands to create the solid model. The second submodule is for specifying tolerances and surface finishes. The designer loads a solid model into the tolerancing submodule and assigns tolerances to various part faces by interactively selecting various faces with the mouse. The graphical interface is build using HOOPS. This involves conversion of the ACIS model to a HOOPS model. The system automatically maintains correspondence between ACIS entities and HOOPS entities. The attribute mechanism of ACIS is used to attach tolerances and surface finishes to various faces.

The machining feature interface module has three main submodules. The first submodule invokes the feature recognition system and collects the parameters of various features in the primary feature set. The second submodule postprocesses the output of the feature recognition system to construct removal

and accessibility volumes of various machining features. The third submodule performs the shape analysis and determines whether the primary feature set is capable of covering the delta volume or not. If the primary feature set does not cover the delta volume completely, then unmachinable portions are identified and displayed on the screen.

The manufacturability analysis module uses features in the primary feature set to generate and evaluate various machining plans. This module has a graphical interface that was built using HOOPS. As various FBMs and plans are generated and evaluated, this interface displays the evaluation results on the screen to keep the designer informed about the progress of analysis. The manufacturability analysis module has six submodule: a submodule that controls the operation of all other submodules, a submodule that generates volumetric covers, a submodule that generates FBMs, a submodule that generates machining plans, a submodule that evaluates machining plans, and a submodule that generates feedback information. If the design is found to be machinable, then the best plan is displayed graphically, and production time decomposition for various part faces is also presented graphically.

10.1.2 Limitations and Restrictions

The main emphasis in this thesis has been to develop a generalized methodology for manufacturability analysis of machined parts. However, due to a large number of practical limitations such as development time, computer resources, software libraries, and so forth, the current implementation has several restrictions on the class of parts handled and the plans generated by the system. Some of the main restrictions are described below.

Implementing offsetting, truncation, and tool selection procedures for generalized milling profiles is a very time consuming task. In the current implementation, only restricted types of milling profiles are handled. The current implementation only allows milling profiles that can be expressed as the union of the following edge-loops: a rectangular edge-loop (with rounded corner) and up to two circular edge-loops.

In case of a through primary feature (i.e., a feature whose bottom is not present in the part boundary), the exact computation of feature depth is a very complicated task. However, for the purpose of manufacturability analysis, in most cases, satisfactory results can be obtained using approximate depths. The current implementation sometimes uses approximations for the depths of through drilling and end-milling features. Thus, some of the features in the primary feature set might only be approximations of the exact primary features.

As described in Chapter 7, one of the steps in generating machining plan is selection of cutting parameters. The current implementation is only capable of selecting the cutting parameters for low-carbon free-machining steels. However, this limitation can be easily overcome by adding cutting parameter data for a broader range of materials.

10.2 Examples

Currently IMACS has been tested approximately on 15 different parts. In Section 10.2.1 we explain how IMACS works on a simple part. Sections 10.2.2 and 10.2.3 provide additional examples to illustrate current capabilities of IMACS.

10.2.1 Example 1: A Socket

Consider the socket shown in Figure 5.14. This socket does not have any thin section or redundant tolerances. As shown in Figures 5.15 and 5.16, 22 primary features are identified for this design. In this case, the extended feature set is the same as the primary feature set. IMACS generates only one volumetric cover for this part. This volumetric cover contains 13 effective removal volumes. Features h11, h12, s9, and s10 have unique effective removal volumes. However, as described in Chapter 6, there are 9 feature pairs that share effective removal volumes. For example, h1 and h2 have the same effective removal volumes. These 9 feature pairs result in $2^9 = 512$ different FBMs corresponding to this volumetric cover. Due to different pruning techniques used in IMACS, only 8 FBMs are actually evaluated. Notice that two pairs of holes in the socket have tight concentricity tolerances. Thus no FBM is evaluated that either involves h11and h8 at the same time. Similarly no FBM is generated that involves h12 and h10 at the same time. Symmetry among various end-milling features creating the fours steps of the socket further reduces the search space (see Chapter 6 for details). Following is the summary of FBM generation as reported by IMACS.

Generating and Evaluating FBMS...

found a FBM: [s9 h12 s10 h11 s3 s5 h9 h4 s7 h2 h6 h7 s1]

PLAN Evaluation->*setup problems* unpromising PRUNED

found a FBM: [s9 h12 s10 h11 s3 s5 h9 h4 s7 h1 h6 h7 s1]

PLAN Evaluation->*setup problems* unpromising PRUNED

- found a FBM: [s9 h12 s10 h11 s3 s5 h9 h3 s7 h2 h5 h7 s1]

 PLAN Evaluation->*setup problems* unpromising PRUNED
- found a FBM: [s9 h12 s10 h11 s3 s5 h9 h3 s7 h1 h5 h7 s1]

 PLAN Evaluation->*setup problems* unpromising PRUNED
- found a FBM: [s9 h12 s10 h11 s3 s5 h10 h4 s7 h2 h6 h8 s1]

 FBM check ->*toler. incomp.* among h8 and h11 PRUNED
- found a FBM: [s9 h12 s10 h11 s3 s5 h10 h4 s7 h1 h6 h8 s1]

 FBM check ->*toler. incomp.* among h8 and h11 PRUNED
- found a FBM: [s9 h12 s10 h11 s3 s5 h10 h3 s7 h2 h5 h8 s1]

 FBM check ->*toler. incomp.* among h8 and h11 PRUNED
- found a FBM: [s9 h12 s10 h11 s3 s5 h10 h3 s7 h1 h5 h8 s1]

 FBM check ->*toler. incomp.* among h8 and h11 PRUNED
- found a FBM: [s9 h12 s10 h11 s4 s6 h9 h3 s8 h1 h5 h7 s2]

 PLAN Evaluation->*updating current-best plan*
- found a FBM: [s9 h12 s10 h11 s4 s6 h9 h3 s8 h2 h5 h7 s2]

 PLAN Evaluation-> unpromising PRUNED
- found a FBM: [s9 h12 s10 h11 s4 s6 h9 h4 s8 h2 h6 h7 s2]

PLAN Evaluation-> unpromising PRUNED

found a FBM: [s9 h12 s10 h11 s4 s6 h9 h4 s8 h1 h6 h7 s2]

PLAN Evaluation-> unpromising PRUNED

found a FBM: [s9 h12 s10 h11 s4 s6 h10 h3 s8 h1 h5 h8 s2]

FBM check ->*toler. incomp.* among h8 and h11 PRUNED

found a FBM: [s9 h12 s10 h11 s4 s6 h10 h3 s8 h2 h5 h8 s2]

FBM check ->*toler. incomp.* among h8 and h11 PRUNED

found a FBM: [s9 h12 s10 h11 s4 s6 h10 h4 s8 h2 h6 h8 s2]

FBM check ->*toler. incomp.* among h8 and h11 PRUNED

found a FBM: [s9 h12 s10 h11 s4 s6 h10 h4 s8 h1 h6 h8 s2]

FBM check ->*toler. incomp.* among h8 and h11 PRUNED

Best FBM: [s9 h12 s10 h11 s4 s6 h9 h3 s8 h1 h5 h7 s2]
Total number of evaluated FBMs: 8

Figures 9.1 and 9.2 show the plan with the best rating for this part as determined by IMACS. Figure 9.3 gives the production time decomposition for various faces that need to be machined.

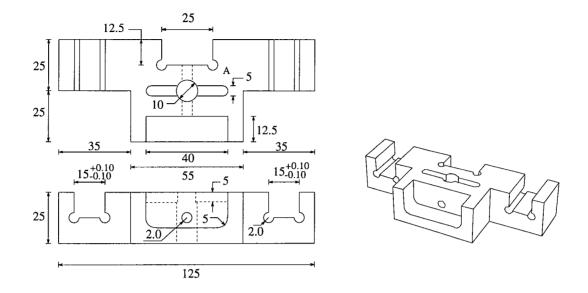


Figure 10.2: Design 1 of bracket.

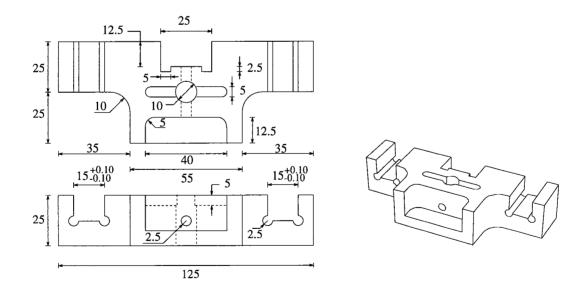


Figure 10.3: Design 2 of bracket.

10.2.2 Example 2: Design of a Bracket

Figures 10.2 and 10.3 show two different designs of a bracket. Let us assume that both these designs will be machined from rectangular stocks of low carbon free machining steel (150 BHN) of size 125mm × 50mm × 25mm. Below are the results of using IMACS to analyze these two designs.

Analysis of Design 1 of bracket. The design shown in Figure 10.2 is machinable. The best plan for this design is shown in Figures 10.4 and 10.5. This design requires 4 setups. Figure 10.6 shows the production time decomposition for various faces to be machined. Theoretically, there are 3392 different FBMs for this design. However, since IMACS uses various pruning heuristics, it examines only 10 of these FBMs. All other FBMs are pruned. The manufacturability rating for this design is 19 minutes.

Analysis of Design 2 of bracket. The design shown in Figure 10.3 is machinable. The best plan for this design is shown in Figures 10.7 and 10.8. This design only requires 2 setups. Figure 10.9 shows the production time decomposition for various faces to be machined. Theoretically, there are 576 different FBMs for this design. However, since IMACS uses various pruning heuristics, it examines only 8 of these FBMs. The manufacturability rating for this design is 17 minutes. Thus, this design is better design than Design 1.

10.2.3 Example 3: Design of a Molding Die Base

Figures 10.10 and 10.11 show two different designs of an injection molding die base. Let us assume that both these designs will be machined from rectangular

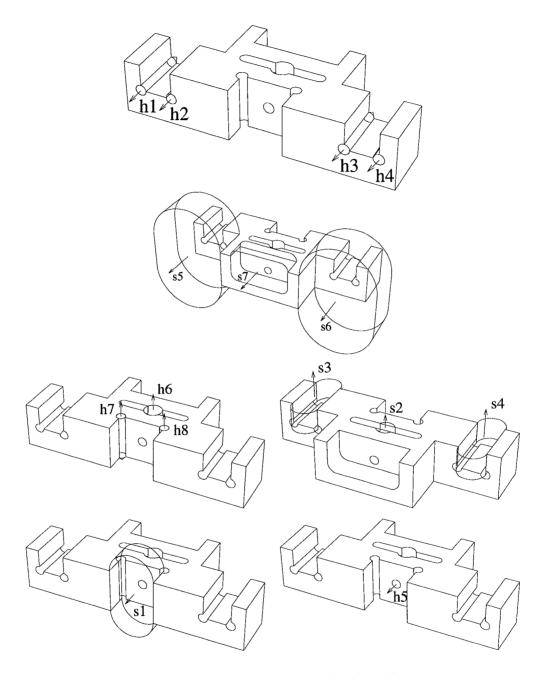
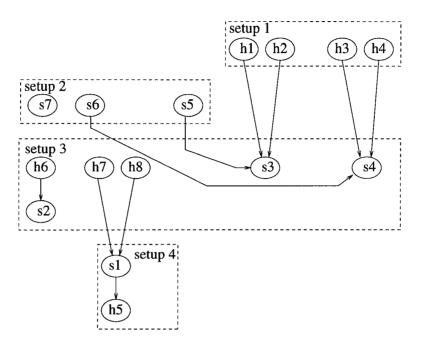


Figure 10.4: Best plan for Design 1 of bracket: feature cover.



details of machining operations

feature	type	tool dia	feed	passes	trajectory length
		(mm)	(mm/min)		(mm)
h1	drilling	4	160	1	26.2
h2	$\operatorname{drilling}$	4	160	1	26.2
h3	$\operatorname{drilling}$	4	160	1	26.2
h4	drilling	4	160	1	26.2
s5	end-milling	50	166	2	75
s6	end-milling	50	166	2	75
s7	end-milling	10	102	3	120
h6	drilling	10	254	1	53
h7	drilling	4	160	1	26.2
h8	drilling	4	160	1	26.2
s2	end-milling	5	81	2	40
s3	end-milling	15	155	2	40
s4	end-milling	15	155	2	40
s1	end-milling	25	166	1	50
h5	drilling	4	160	1	26.2

Figure 10.5: Best plan for Design 1 of bracket: details of operations.

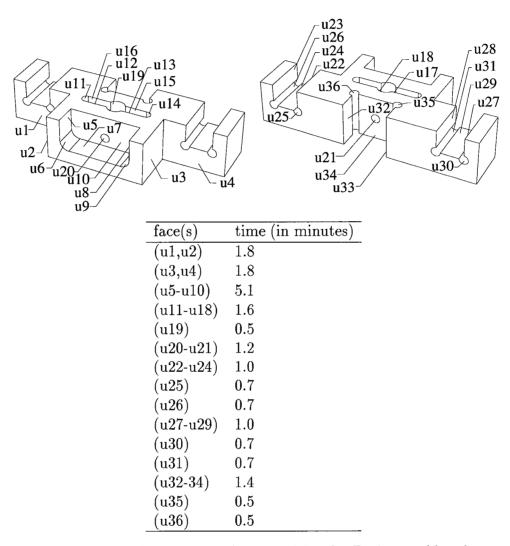


Figure 10.6: Production time decomposition for Design 1 of bracket.

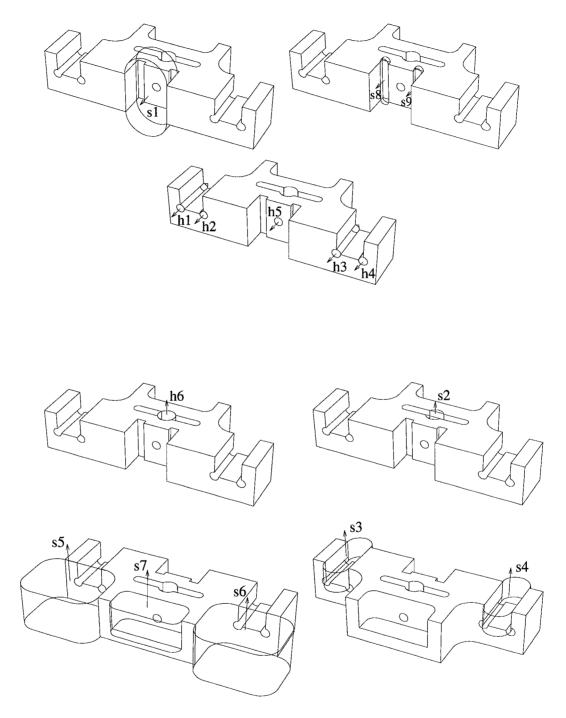
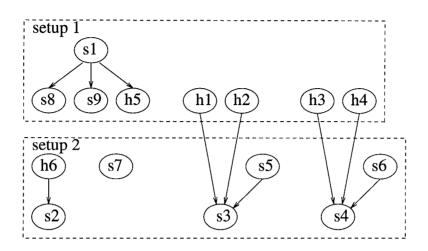


Figure 10.7: Best plan for Design 2 of bracket: feature cover.



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feature	type	tool dia	feed	passes	trajectory length
		(mm)	(mm/min)		(mm)
$\overline{s1}$	end-milling	25	166	1	50
s8	end-milling	5	81	1	30
s9	end-milling	5	81	1	30
h1	drilling	5	160	1	26.5
h2	drilling	5	160	1	26.5
h3	$\operatorname{drilling}$	5	160	1	26.5
h4	$\operatorname{drilling}$	5	160	1	26.5
h5	$\operatorname{drilling}$	5	160	1	26.5
h6	drilling	10	254	1	53
s2	end-milling	5	81	2	40
s5	end-milling	20	173	3	90
s6	end-milling	20	173	3	90
s7	end-milling	10	102	4	80
s3	end-milling	15	155	2	40
s4	end-milling	15	155	2	40

Figure 10.8: Best plan for Design 2 of bracket: details of operations.

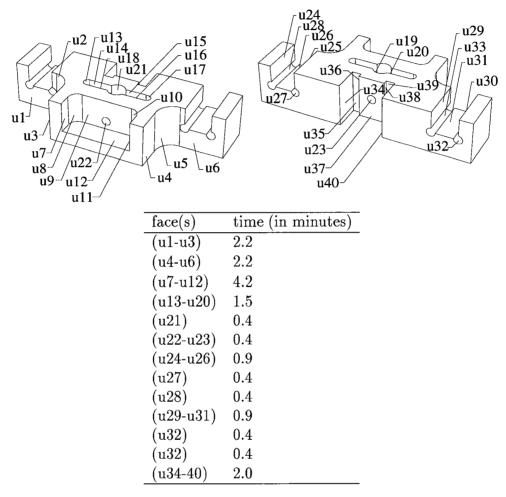


Figure 10.9: Production time decomposition for Design 2 of bracket.

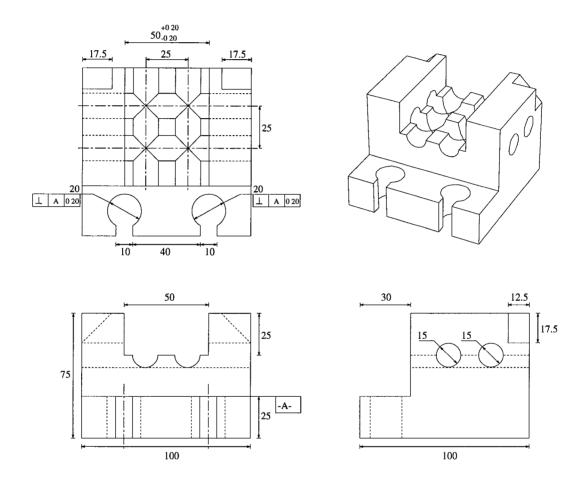


Figure 10.10: Design 1 of die base.

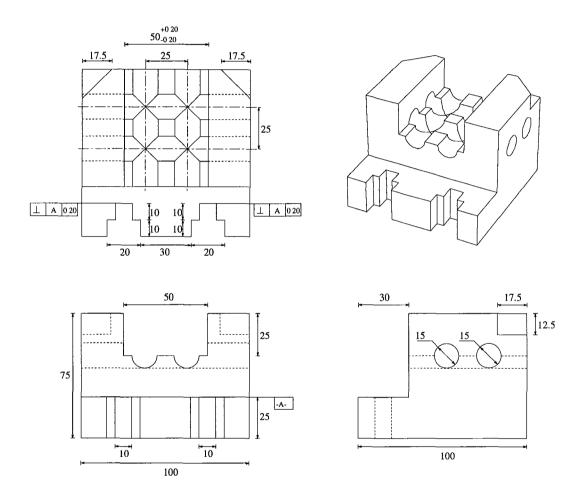


Figure 10.11: Design 2 of die base.

stocks of low carbon free machining steel (150 BHN) of size $100 \text{mm} \times 100 \text{mm} \times 75 \text{mm}$. Below are the results of using IMACS to analyze these two designs.

Analysis of Design 1 of die base. The design shown in Figure 10.10 is machinable. The best plan for this design is shown in Figure 10.12 and 10.13. This design requires 3 setups. Figure 10.14 shows production time decomposition for various faces to be machined. Theoretically, there are 8192 different FBMs for this design. However, since IMACS using various pruning heuristics, it only examines 112 of these FBMs. Manufacturability rating for this design is 16 minutes.

Analysis of Design 2 of die base. The design shown in Figure 10.11 is machinable. The best plan for this design is shown in Figures 10.15 and 10.16. This design also requires 3 setups. Figure 10.17 shows production time decomposition for various faces to be machined. Theoretically, there are 128 different FBMs for this design. However, since IMACS using various pruning heuristics, it only examines 8 of these FBMs. The manufacturability rating for this design is 15 minutes. Thus, this design is better than Design 1. One more thing worth noticing here is that though this design is similar to Design 1, but the best plan for this design is considerably different from the best plan for Design 1.

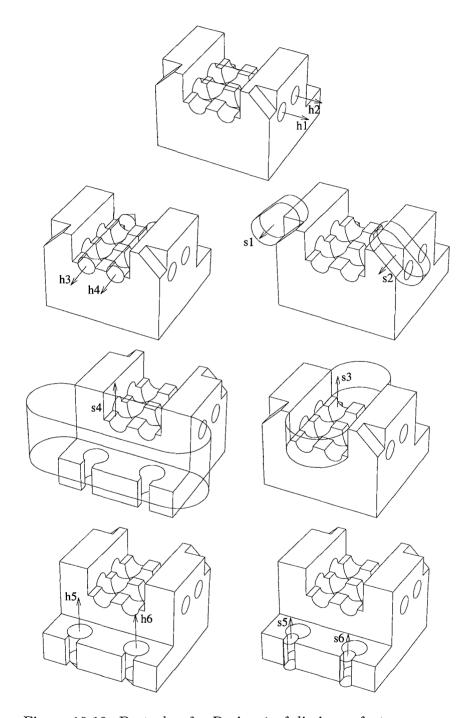
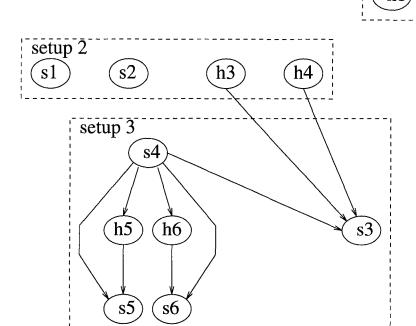


Figure 10.12: Best plan for Design 1 of die base: feature cover.



setup 1

details of machining operations trajectory length feature type tool dia feed passes (mm) (mm/min) (mm)258 $\overline{h1}$ drilling 15 1 104.5h2drilling 1 104.5 15 258h3drilling 15 2581 74.5h4drilling 15 258 1 74.5 s1end-milling 25 166 1 50s2end-milling 25 166 1 50 3 s4end-milling 50 166 150 2 s3end-milling 50 166 120 h520 1 drilling 244 26 h6drilling 20 2441 26 end-milling s510 102 5 15 5 s6end-milling 10 102 15

Figure 10.13: Best plan for Design 1 of die base: details of operations.

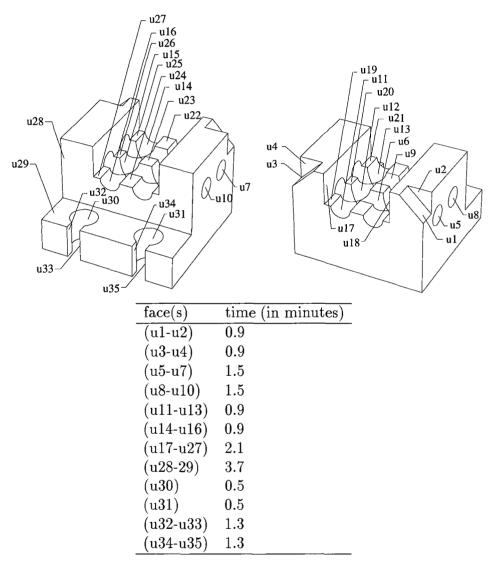


Figure 10.14: Production time decomposition for Design 1 of die base.

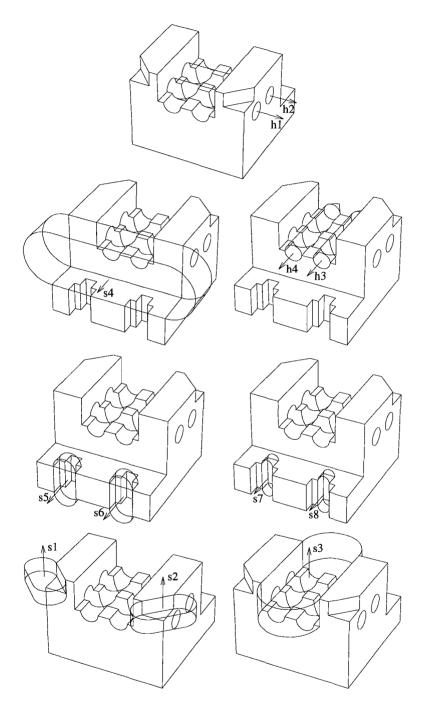
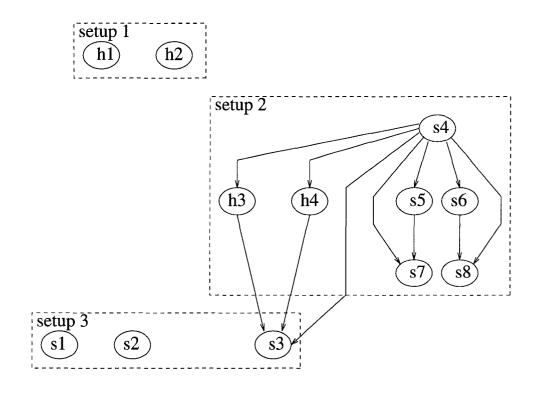


Figure 10.15: Best plan for Design 2 of die base: feature cover.



details of machining operations					
feature	type	tool dia	feed	passes	trajectory length
		(mm)	(mm/min)		(mm)
h1	drilling	15	258	1	104.5
h2	$\operatorname{drilling}$	15	258	1	104.5
s4	end-milling	50	166	2	150
h3	drilling	15	258	1	74.5
h4	$\operatorname{drilling}$	15	258	1	74.5
s5	end-milling	20	153	1	40
s6	end-milling	20	153	1	40
s7	end-milling	10	102	2	30
s8	end-milling	10	102	2	30
s1	end-milling	25	166	1	50
s2	end-milling	25	166	1	50
_s3	end-milling	50	166	2	120

Figure 10.16: Best plan for Design 2 of die base: details of operations.

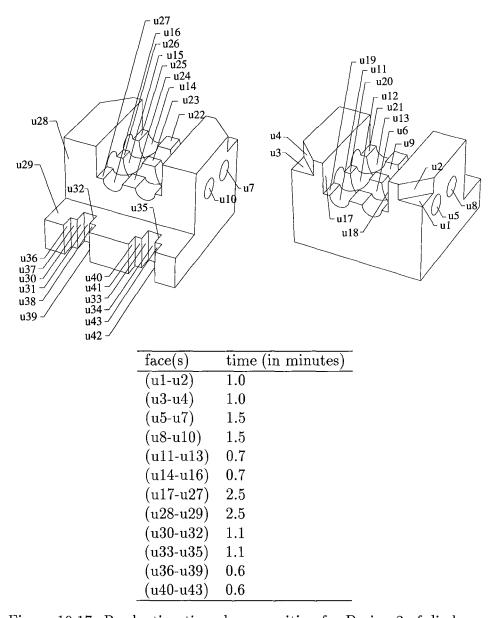


Figure 10.17: Production time decomposition for Design 2 of die base.

Chapter 11

Conclusions

11.1 Research Contributions

The preceding chapters have presented a systematic methodology for computerized manufacturability analysis of machined parts. Manufacturability analysis provides feedback to the designer about possible manufacturability problems, thereby providing an opportunity to modify the product to improve its manufacturability characteristics.

The approach developed in this thesis is based on the systematic exploration of various machining plans. First various features are recognized that can potentially be used to machine the given design. Then, using these features, different machining plans are generated and evaluated. The manufacturability rating of the design is based on the rating of the best plan. If no feasible plan can be found, then the design is considered unmachinable. In case of unmachinable designs, the design attributes, posing the machining problems are identified.

The approach presented in this thesis is superior to previous approaches in the following two aspects. First, since various alternative ways of machining the part are considered in this approach, the conclusions about the manufacturability are more realistic compared to the approaches in which just one alternative is considered. Second, most previous approaches had difficulties in generating the correct plans for the part that involved intersecting tool swept volume for various machining operations. This approach is capable of handling such parts.

The main research contributions of this thesis are summarized below.

1. A new approach to defining and classifying machining features. In order to perform automated manufacturability analysis, design attributes need to be interpreted in terms of manufacturing operations that can be used to create them. Typically, features are used for this purpose. In previous approaches, the feature definition lacked several critical pieces of information needed for manufacturability analysis. In this thesis, a variety of process related information such as accessibility, tooling, dimensional constraints and so forth, has been incorporated into the definition of machining features. This new definition maintains direct correspondence between features and machining operations. Thus, the machining features defined in this thesis can be used for analyzing the realizability of various machining operations associated with the features.

For a given part, there often can be a very large (in some cases, infinite) number of feature instances. However, only a small number of instances are useful in practical machining plans. This raises the question — what features should be recognized? In previous approaches this issue has not been addressed. In this thesis, the notion of a primary feature has been introduced to handle this issue. For any given part, only primary features need to be recognized. All useful machining plans can be generated by

manipulating the primary features. For every part, there are only a finite number of primary features. This helps in improving the efficiency of feature identification.

2. A systematic approach for examining alternative machining plans.

Most existing CAD/CAM systems try to generate a single plan for a given part—but in order to do accurate manufacturability analysis, alternative machining plans need to be examined in a systematic way. There has been very little previous research in the area of systematic examination of alternative machining plans. In this thesis, a systematic approach has been developed to explore various alternative machining plans. This approach is based on the generate-and-test methodology. Various machining plans are generated and evaluated to determine which of the alternatives is most preferable. Different interpretations, representing the part as alternative collections of machining features, are generated. These interpretations are used to generate various machining plans. Estimation of machining accuracy and production time is used to discard the unpromising plans.

3. Pruning techniques for handling the combinatorial explosion during plan generation. For complicated parts, generating all possible machining plans is computationally very expensive. In most of the realistic cases, very few of the possible alternatives are of any practical use. In this thesis, a variety of criteria such as machining time, tolerances, dimensional constraints, fixturability etc. are used for judging the merit of plans. These criteria are used to define pruning heuristics that are used to discard machining plans with excessive production time. Various pruning heuristics are used in conjunction with a branch-and-bound strategy. During vari-

ous stages of plan generation, a number of evaluations are performed. At any stage, if a plan is found to be worse than the current-best plan, then the plan is discarded. Various pruning techniques help in controlling the combinatorial explosion during plan generation.

- 4. An approach for manufacturability analysis of design tolerances.
 - Designers specify tolerances to describe the permissible variations on the design's geometry. These tolerances affect the process planning significantly. In most existing generative process planning systems, process capabilities of machining processes are compared with the specified tolerances to select the machining process. However, in case of geometric tolerances, setup sequences play a major role in determining whether or not a specified tolerance is achievable. In this thesis, an approach has been developed to compare achievable machining accuracy with the design tolerance in presence of precedence constraints. This helps in analyzing the manufacturability a design tolerance.
- 5. A mechanism for generating manufacturability feedback. Usefulness of a manufacturability analysis system is determined by the nature of the feedback information offered to the designer. In this thesis, a mechanism has been developed to offer the manufacturability feedback during various stages of analysis. Various design attributes such as shape, dimensions, tolerances and so forth are analyzed for possible manufacturability problems. If any design attribute is found to be unmachinable, it is included in the feedback information along with the probable cause of the machining problem.

The manufacturability ratings used in this thesis are based on production time. These ratings present a realistic view of the difficulty in manufacturing a proposed design. These ratings are specially useful if the designer is using more than one manufacturability analysis system (for example, one for machining and the other one for assembly). In such cases, the ratings based on production time can easily be combined into an overall rating.

11.2 Anticipated Impact

The goal of this research is to provide tools for manufacturability analysis as part of the CAD systems used by designers. Even if designers have access to such tools, the ultimate cost and quality of the product will still depend on the designer's creativity and ability. However, it is expected that this research will help in improving the productivity of designers, by helping them to design products that are less expensive to manufacture. This will reduce the need for redesign, resulting in reduced lead time and product cost.

The information produced by manufacturability analysis can be used in the following two ways.

1. **Design.** When a designer proposes a design of a machinable part, this analysis will allow him/her to see the alternative ways in which it might be machined, to obtain information what tolerances are achievable, and to predict if the achievable tolerances will become better or worse as the feature dimensions are changed. The approach developed in this thesis provides the designer with information on the relevant production time, in order to balance the needs for efficient manufacturing of a quality product.

Such an ability to study and evaluate a proposed design aids the goals of concurrent engineering, by pushing the manufacturing concerns upstream into the design stage. Therefore, it is expected that this research will provide a powerful tool for engineering designers.

2. **Process planning.** The procedures for generating alternative machining plans provide a powerful consultation tool for the production engineer to use during process planning. It offers information about what processes are most desirable over the various ways in which a part might be machined.

We anticipate that the results of this research will be useful in providing a way to speed up the evaluation of new product designs in order to decide how or whether to manufacture them. Such a capability will be especially useful in flexible manufacturing systems, which need to respond quickly to changing demands and opportunities in the marketplace.

11.3 Recommendations for Future Work

In order to build a practical manufacturability analysis system for real-life parts, several extensions will be needed to this research. Below are the some of recommendations for future extensions.

1. Better pruning techniques. In order to handle more complicated parts, more effective pruning techniques will be needed. One way to achieve effective pruning is to perform the planning for non-interacting portions of the design independently. Different plans for various portions of the design can be later combined into a single plan. More effective pruning techniques will

be needed for discarding unpromising feature-based models and machining plans. For example, tolerance information can be used during feature identification to discard features having unpromising orientations.

- 2. Improved production cost and time models. In this thesis, a number of approximations have been made in estimating the production time. In order to get better manufacturability ratings, the estimation of production time will require several improvements. For example, a number of factors in auxiliary time such as tool change time, tool idle movement, and so forth, can be estimated with better precision. Moreover, an extension of the setup estimation procedure will be needed to incorporate a more realistic estimation of setup time.
- 3. Improved machining accuracy models. Most of the machining accuracy data used in this thesis has been collected from handbooks and applies to a wide classes of machine tools. However, in actual practice, machining accuracy closely depends on the specific machine tool. Thus, general purpose machining accuracy data is not very reliable. Better machining accuracy models are needed to account for the variations in the specific production environment.
- 4. Complexity study. In the worst case, a part may have an exponential number of FBMs, and hence an exponential number of machining plans. Thus, a brute-force approach to generating and evaluating operation sequences would take exponential time. In our approach, the pruning heuristics will prevent most of these FBMs and machining plans from being generated—but it still seems possible that our approach will generate

and evaluate an exponential number of alternatives in the worst case. It is doubtful that any other approach can do any better, because the problem of finding an optimal machining plan is likely to be NP-hard. However, in order to tell for sure, detailed complexity studies should be done for both the problem and our approach.

- 5. Automated fixturability analysis. In this thesis, fixturability issues were not considered. In order to have a complete manufacturability analysis system, a fixturability analysis system will also be needed. The fixturability analysis system should be capable of analyzing the design for fixturability problems, and should be fully intergrated with the system developed in this thesis.
- 6. Inclusion of primary processes. Many real-life parts are produced using a combination of primary and their secondary processes. For example, engine blocks are first cast, and then machined to their final shape. In many cases, manufacturability requirements for different processes are very different. For example, a design shape that is easy to cast may pose problem during fixturing. Incorporating more then one type of manufacturing processes in the same manufacturability analysis system is a challenging research problem. As an extension of the current work, a manufacturability analysis system will be needed that handles different combinations of manufacturing processes.
- 7. Automated design improvement. After analyzing the manufacturability, the next step is to automatically formulate the suggestions for improving the manufacturability of the design. Developing a fully automated

system for design improvement will probably be quite difficult, as this will require capturing the complete design intent and functionality. However, a number of commonly occurring manufacturability problems, requiring minor design modifications can be corrected automatically.

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

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